A LOW COST, MICROPROCESSOR-BASED BATTERY CHARGE CONTROLLER

RENEWABLE ENERGY BRANCH

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Energy, Mines and Resources Canada
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PREPARED BY:
D.L.Pulfrey and J.Hacker
Pulfrey Solar Inc.
4030 West 35th Avenue
Vancouver, B.C. V6N 2P3
Telephone: (604) 228-3876

SCIENTIFIC AUTHORITY:
J.L. McClung
Solar Energy Development Program
Renewable Energy Branch

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ABSTRACT

This report describes the design, construction, testing and evaluation of a microprocessor-based battery charge controller which uses charge integration as the method of battery state-of-charge estimation. The controller is intended for use in medium-size (100-1000Wp) photovoltaic systems which employ 12V lead-acid batteries for charge storage. The controller regulates the charge flow to the battery and operates in three, automatically-determined modes, namely: charge, equalize and float. The prototype controller is modular in nature and can handle charge/discharge currents of magnitude up to 80A, depending on the number of circuit boards employed. Evaluation tests and field trials have shown the controller to be very accurate and reliable. Based on the cost of the prototype, it appears that an OEM selling price of $400 for a 40A (500Wp) unit may be realistic.

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EXECUTIVE SUMMARY

The objective of the work described in this report is to establish the practicability of incorporating a battery charge controller, which uses charge integration as the method for estimating the state-of-charge of 12V lead-acid batteries, in medium-size (100-1000Wp) photovoltaic systems.

The prototype controller developed for this purpose is based on a CMOS 6805 microprocessor and provides for three modes of operation, namely: battery charging at the available array current; equalization of the state-of-charge (SOC) of the cells within the battery by allowing "overcharging" to the extent of 5% of the cumulative discharge since the previous instance of full-charge; and floating (trickle charging) of the battery after completion of the equalization charging period.

In addition to the standard overcurrent protection and voltage surge suppression features afforded by fuses and varistors, respectively, the controller's software provides signals to limit the battery terminal voltage to 17.5V during the charge and equalization modes and to 14V during the float mode. As a further protective measure, the minimum allowable SOC can be set to a user-selectable level. Also user-selectable are the battery capacity and its initial SOC. These are required input parameters in the initialization procedure for the controller, and are stored in the RAM of the microprocessor. The system code is stored in an EPROM.

The controller circuitry is partitioned into two circuit boards. The logic board, which contains the control chips and an LCD display, and a power board, which contains the power supplies, instrumentation, signal processing and power-switching circuitry. Each power board is rated at 20A, and a single logic board can service up to 4 power boards. This concept of a modular controller allows for the easy assembly of units rated from 20A to 80A. Thus, a unit with a

single power board would be suitable for PV systems rated up to 250Wp, while a unit with four power boards could service PV systems rated up to 1000Wp.

A single power board, prototype controller, rated at 20A, has been designed, constructed and tested. The evaluation tests have shown that the charge integration method of SOC estimation is more accurate than the traditional methods based on either the specific gravity of the electrolyte or the terminal voltage of the battery. Field trials of the controller, using a 330W array on the roof of BC Hydro's R&D facility, have shown the controller to be durable and reliable.

A "preproduction", 80A (1000Wp) version of the controller has been assembled as the contract deliverable. From the costs involved it appears as if an OEM selling price for a 40A (500Wp) version of around $400 may be realistic. Such a price should give the controller a distinct market edge in those medium power terrestrial applications where accuracy, reliability and flexibility are important, e.g. navigational aids, warning systems and communications networks.

1.0 INTRODUCTION

All photovoltaic (PV) systems employing batteries need some form of battery charge control. At the simplest level this involves merely a shunt regulator. The Solar Sentry from BOSS, and the PBR-12 from SunAmp Systems are typical examples of 100Wp models, see Appendix 1. Such controllers cost around $150 and are usually employed in small PV systems as they constitute an acceptable fraction of the systems' total cost, e.g. about 20% for a 50Wp system.

For much larger PV systems, several kilowatts or so, it is cost effective to employ more expensive control units. The MAC microprocessor unit developed by Trisolar is a prime example, see Appendix 1. It sells for around $US12,000 and has a multiplicity of features. It monitors the charge flow to and from the battery and, in addition to controlling the charging of the battery, it has the capabilities of modifying the module connections within an array, implementing a maximum power point tracker, shedding loads, displaying the battery state-of-charge and other system parameters on a LCD, performing self-test routines and data-logging.

There is presently no controller which occupies the middle ground between the extremes of costs, system ratings and sophistication delineated by the above two types of controller. However, there is a need for such a controller in medium-size PV systems (100 -1000Wp), where the features of reliability, accuracy, flexibility and efficiency, usually only found in up-market controllers, are required. Such applications cover all terrestrial installations servicing important functions in the critical areas of, for example, navigational aids, warning systems and communications networks.

Attainment of the desirable features listed above depends, to a large extent, on selecting a suitable method for estimating the state-of-charge of the

battery. Many possible methods have been tried in the past, namely: measurement of physical properties of the electrolyte such as PH, specific gravity, humidity, refractive index; measurement of electrical properties such as terminal voltage, integrated charge flow and impulse current response; and auxiliary methods using satellite cells. The methods based on the external electrical measurements of either terminal voltage or integrated charge flow are the most practical to implement in an operational system.

It is noteworthy that the terminal voltage measurement method, used in all shunt regulator controllers, is considerably less accurate than the charge flow method. This is because the battery terminal voltage depends markedly on the battery's past history, particularly on its rate of charging and electrolyte temperature. Further, the terminal voltage method does not provide a sensitive means of catering for the equalization and float modes of operation. These two modes, if properly exploited, can greatly prolong a battery's life.

The question that arises, therefore, is: can a battery charge controller based on the integrated charge flow method be built such as to satisfy the demands of 100-1000Wp PV systems and sell for around $500? This report describes a project which sought to answer this question.

2.0 OBJECTIVE

The objective of the work described in this report was:

> to design, construct and evaluate a charge controller for 12V lead-acid batteries, based on the integrated charge flow method of state-of-charge estimation, which will fill the market niche which lies between those low power applications where simple, shunt regulating controllers are presently used and those high

power applications where sophisticated, multi-functional microprocessor automatic controllers are presently used.

3.0 METHODOLOGY

3.1 The Controller

3.1.1 *General features*

To meet the objective quoted above, the controller must carefully control battery charging, must accurately display the state-of-charge (SOC), must be able to accommodate system expansion, and must be reliable and efficient. In addition, a 500Wp version of the controller should sell for around $400.

To satisfy these criteria a modular design has been implemented in which the controller is partitioned into separate power and logic boards. The logic board is capable of servicing up to 4 power boards. As each power board is rated at 20A, this gives the controller a rating range of 240Wp to 960Wp, depending on the number of power boards employed.

The battery current control scheme involves three modes of operation, namely: charging at the current level being supplied by the array; providing an equalization charge; supplying a trickle charge. The mode flowchart is shown in Figure 1. The code to implement this control scheme is stored in an EPROM on the logic board. The operative mode is determined by the battery SOC. This is continuously evaluated by integrating the charge/discharge current using high resolution counters.

If SOC < 100% the controller is in charge mode. Any discharge will cause the internal charge counter to decrement in direct proportion to the computed

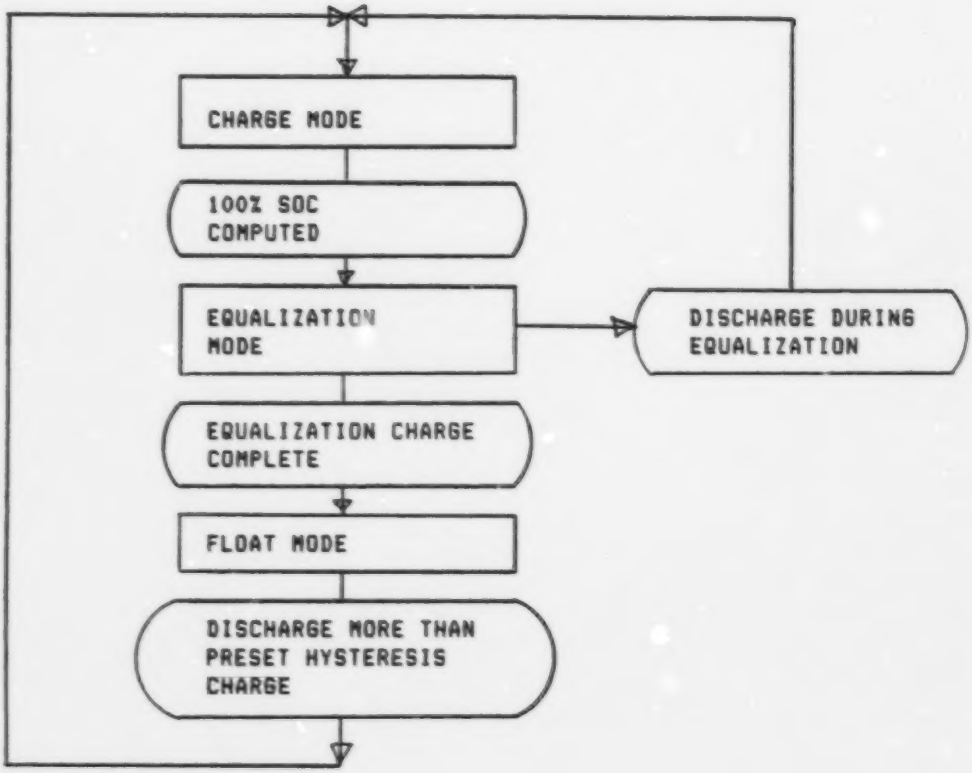


Figure 1: Mode flow chart

charge flow. Any charging will increment the counter in proportion to the product of the computed charge flow and a temperature-dependent charging efficiency factor. This factor can be evaluated from data supplied by the battery manufacturer, or from practical experience, and is stored in system memory as a lookup table. A value of 0.9 appears to be satisfactory for most purposes.

When SOC= 100%, the controller switches to equalization mode. The battery is charged by the available array current to an extent based on the total cumulative discharge which has occurred since the battery was last fully charged. Presently, the equalization charge is set at 5% of the cumulative discharge, up to a maximum of 5% of the rated battery capacity.

After equalization is complete, the controller enters the float mode and supplies a trickle charge to the battery. If the load should exceed the trickle charge, the battery discharges. An uninterrupted discharge of 0.5 Ah causes the controller to switch into the charge mode, whereupon the cycle repeats.

3.1.2 *Hardware*

The controller circuitry is partitioned into separate power and logic circuit boards. Photographs of the prototype boards are shown in Figure 2.

The power board contains subsystems for battery current control, current blocking during periods of low insolation, voltage limiting of battery potential during the float mode of operation, generation of current, voltage and temperature signals for processing by the logic board, lightning protection in the form of a voltage surge suppressor (metal oxide varistor) and the power supply to run the controller circuitry. In controllers utilizing more than one power board, the second and subsequent power boards do not need to include the power supply feature and the temperature and voltage instrumentation. A block

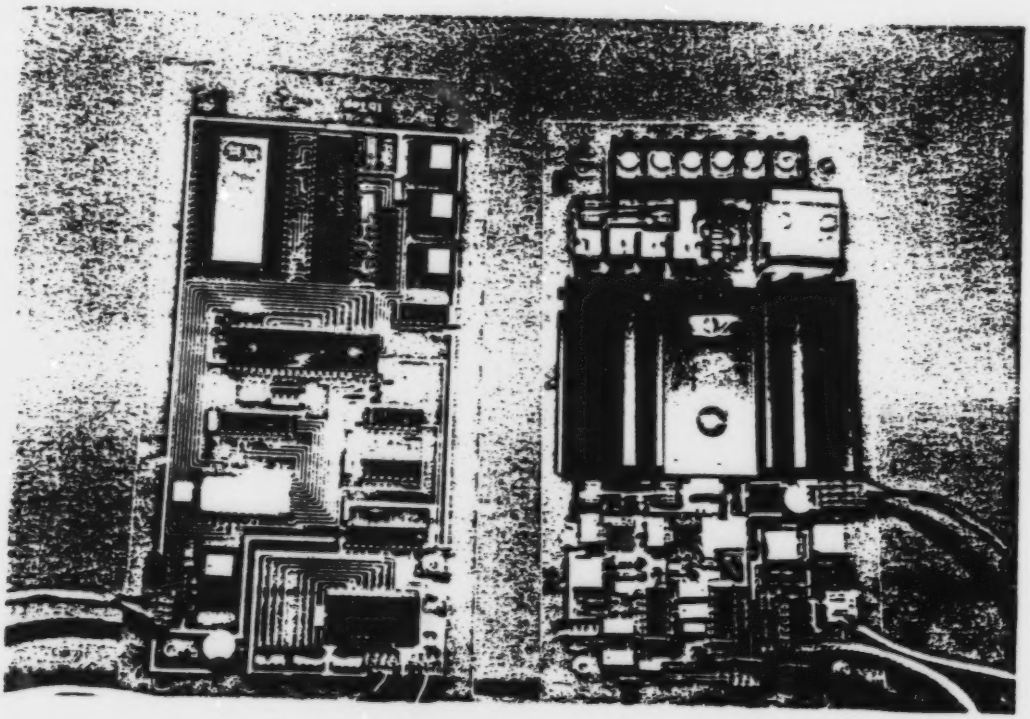


Figure 2: Photographs of the logic board and the main power board for the Mark II controller. The logic board (left) measures 22.2cm x 11.7cm and the power board (right) measures 21.2cm x 11.7cm.

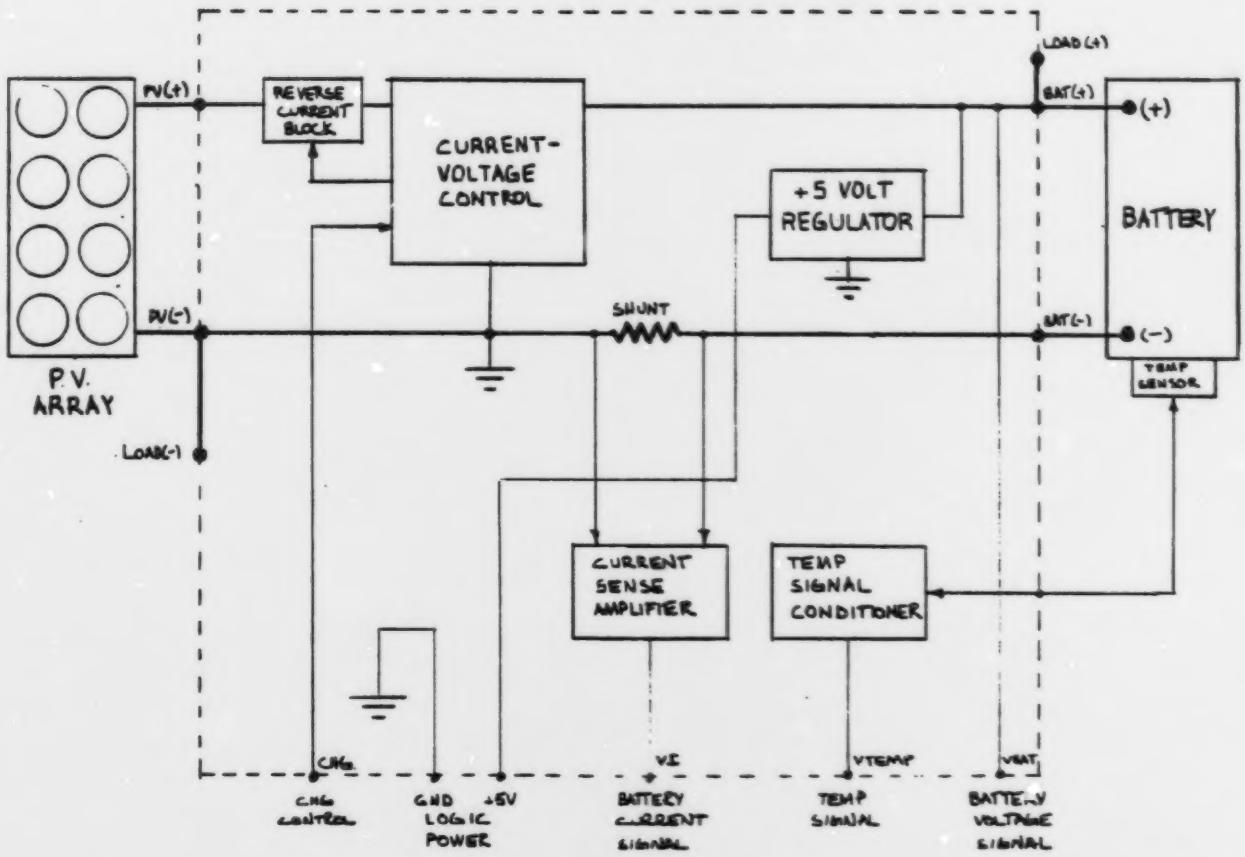


Figure 3: Block diagram of the power board.

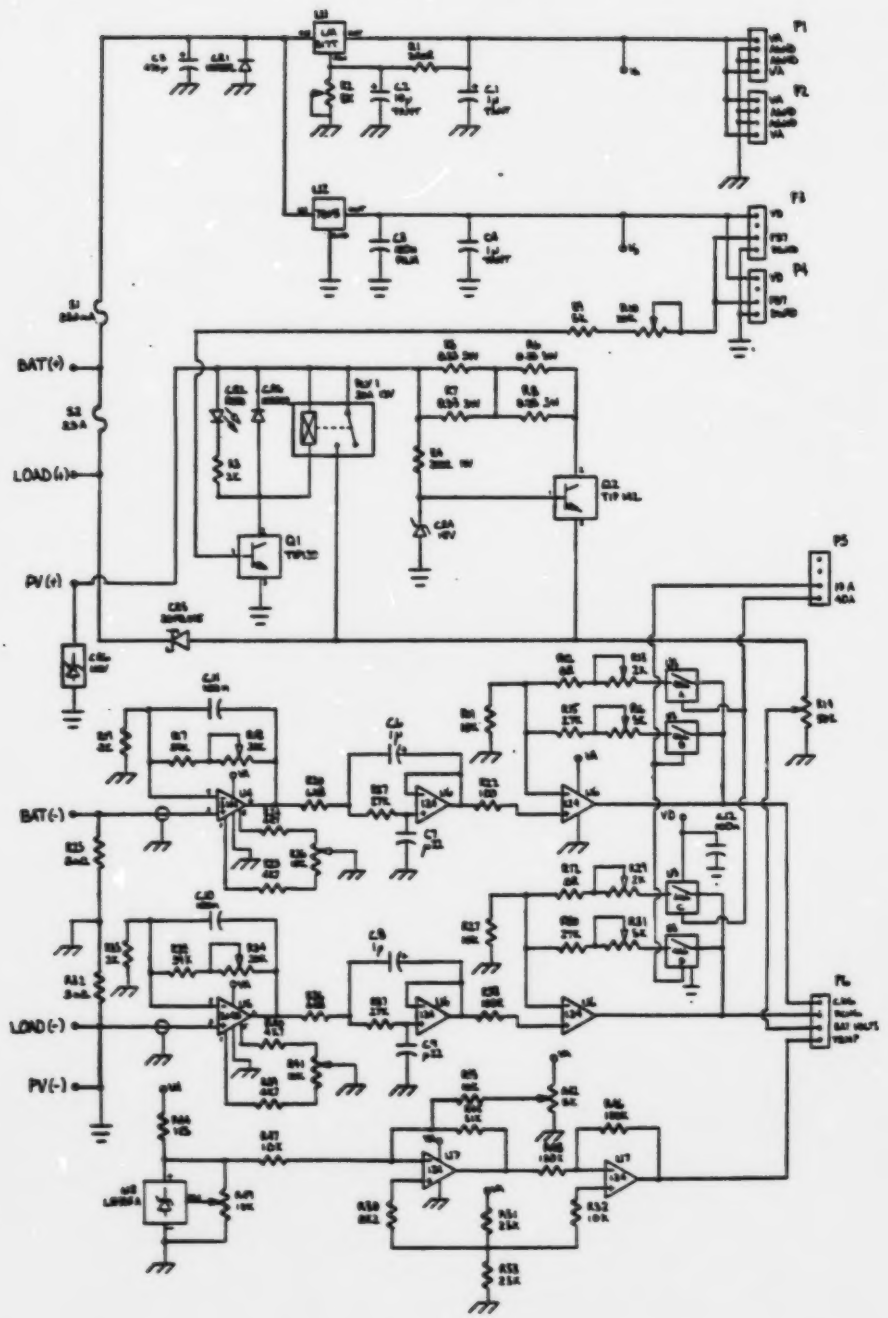


Figure 4: Schematic of the main power board circuitry.

diagram of the power board is shown in Figure 3, and a detailed schematic is given in Figure 4.

Particular attention has been paid in the circuit design to the elimination of problems due to noise. To this end, the analog and digital power supplies have been completely isolated and active, second-order, Chebyshev, low pass filters (f_c=20Hz) have been incorporated after each current sense amplifier. Programmable gain stages are inserted after the low pass filters to allow for current auto-ranging. This feature allows peak currents of up to 40A per power board to be measured, without sacrificing resolution at low current levels. The linearity of the current conversion at low currents is good because of the use of high quality OPAMPs (CA3140E), which allow offset voltage nulling. The entire dynamic range of the A/D converter is utilized by setting the analog power supply at 1.5V above that of the digital power supply.

The power board circuitry provides four control signals which are processed by the logic board, namely: VBAT, the battery voltage; VI+, the battery charge current; VI-, the battery discharge current, and VTEMP, the battery case temperature. The logic board circuitry processes the signals from the power board and returns the signals for charge mode selection to the power board. In addition, it generates the percent state-of-charge (SOC) display information and provides the input data for initialization of the system at start-up and on reset. A block diagram of the logic board is shown in Figure 5 and a circuit schematic in Figure 6.

In keeping with the need to minimize power consumption, all the chips on the logic board are of the CMOS variety. The heart of the circuit is a 6805-based microcomputer chip. Supporting this versatile component are an EPROM, LCD display and driver, and A/D circuitry to interface with the instrumentation of the power board. The analog multiplexer has 16 channels, enough to interface with four power boards.

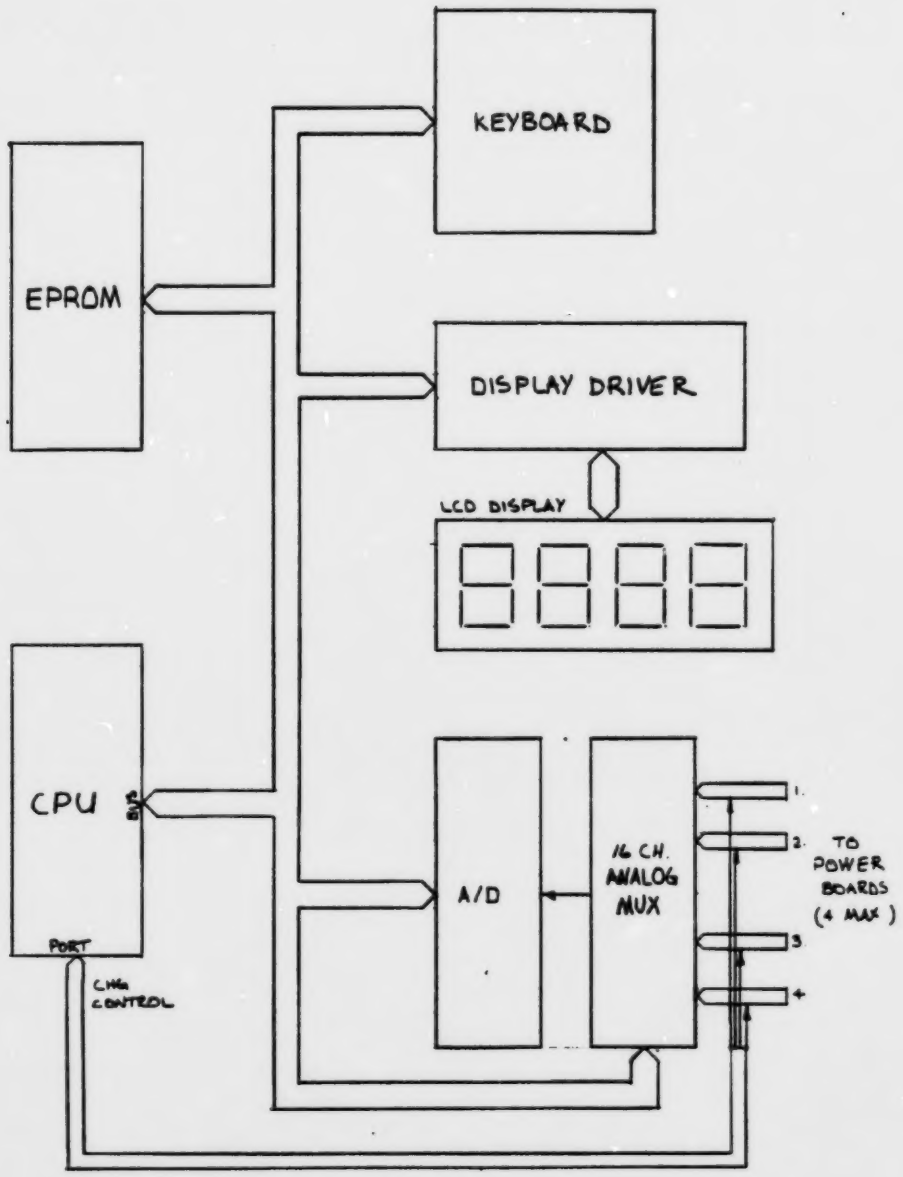


Figure 5: Block diagram of the logic board.

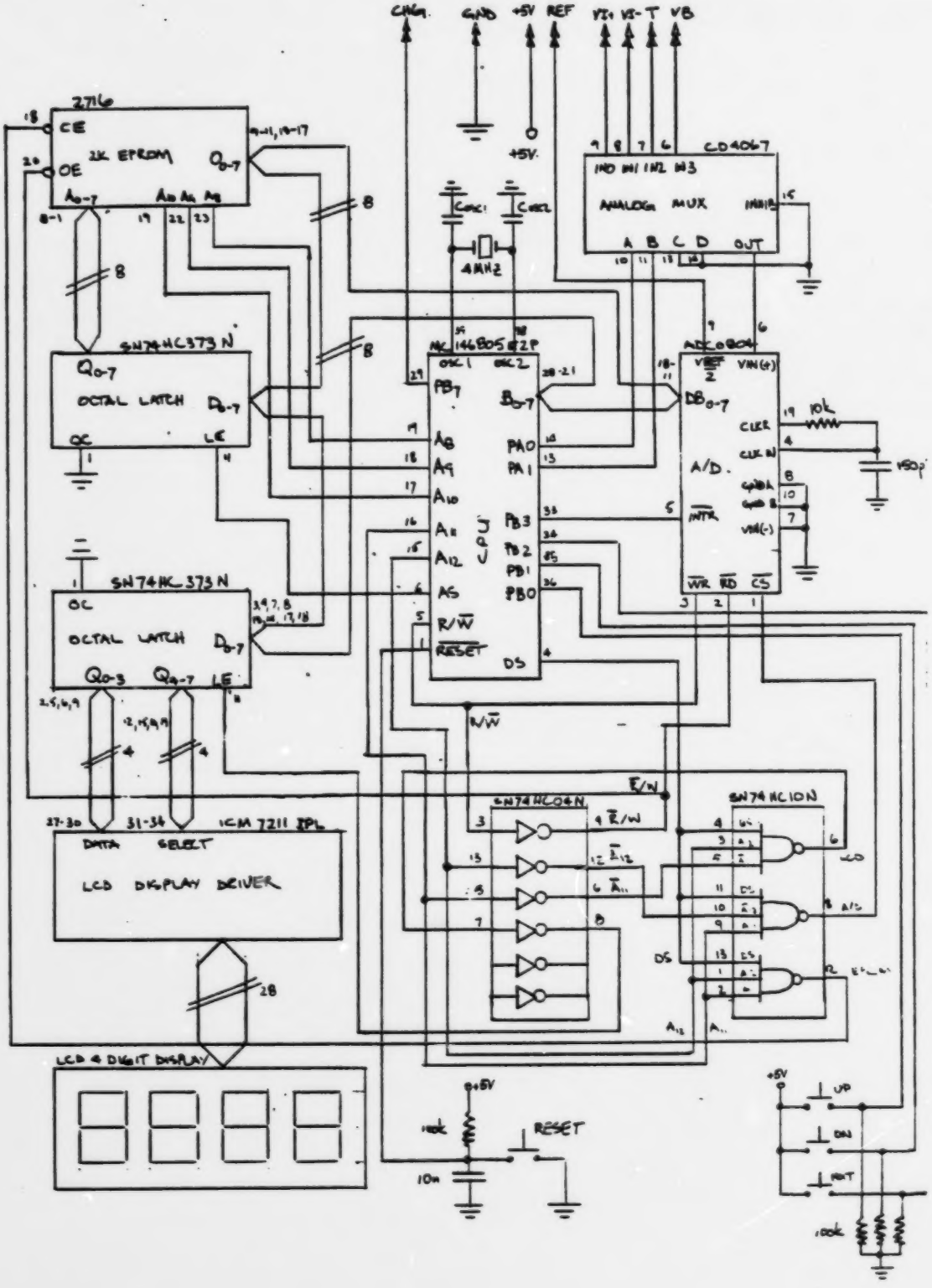


Figure 6: Schematic of the logic board circuitry.

System parameters, other than just the battery SOC, can be displayed on the LCD. These parameters, which perform a useful diagnostic function, are listed in Table 1, along with their respective activating combinations of switch positions. The switches are located on the logic board, see Figure 2.

The power and logic boards of the prototype are housed in a NEMA class 4 enclosure (model no. 1414 N4 PH from Hammond). This steel box has a piano hinge lid which seals against a neoprene gasket. It is water-tight, dust-tight and meets CSA standards (nos. LR21001 and LL21312) for housing electric equipment out-of-doors. Connections to the battery and array are made via two inverted L-shaped conduits which embrace two 1-inch holes in the side of the box. Figure 7 shows a photograph of the enclosure. The interface between the leads from the external components (the array, battery and load) and the internal circuitry occurs at the heavy-duty terminal strip shown in the picture. Also visible is a separately-mounted relay subcircuit. This guards against the discharging of the battery below its point of charge/discharge reversibility. The circuitry for this protective feature is shown in Figure 8. When the SOC declines to a preset level, the microprocessor issues a LOAD CMD signal which turns-off transistor Q1, thus deactivating the relay and shedding the switchable load.

3.1.3 *Software*

The software to operate the controller requires 2 kbytes of code and is stored in the EPROM. The program flowchart is shown in Figure 9.

The CPU clock frequency is 4MHz and the CPU cycle frequency is 0.8 MHz. An 8-bit counter with a divide-by-eight prescaler is used for the sampling time base. The battery current is sampled on every 25th interrupt of the timing counter, giving a sampling interval of 1.024 sec. The battery current

TABLE 1: Diagnostic Display Functions

Switches			Parameter	Function
Up	Down	Next		
0	0	0	SOC	displays SOC (%)
0	0	1	DISCHG	displays discharge current (HEX)
0	1	0	CHG	displays charge current (HEX)
0	1	1	HISOC	displays SOC, hi-resolution (HEX)
1	0	0	BATCAP	displays battery capacity (Ah)
1	0	1	CUMDCHG	displays cumulative discharge since the system was last in float mode (HEX)
1	1	0	SOCTRA	displays present value of SOC register (HEX)
1	1	1	TEMP/VOL	displays battery temperature and voltage (HEX)

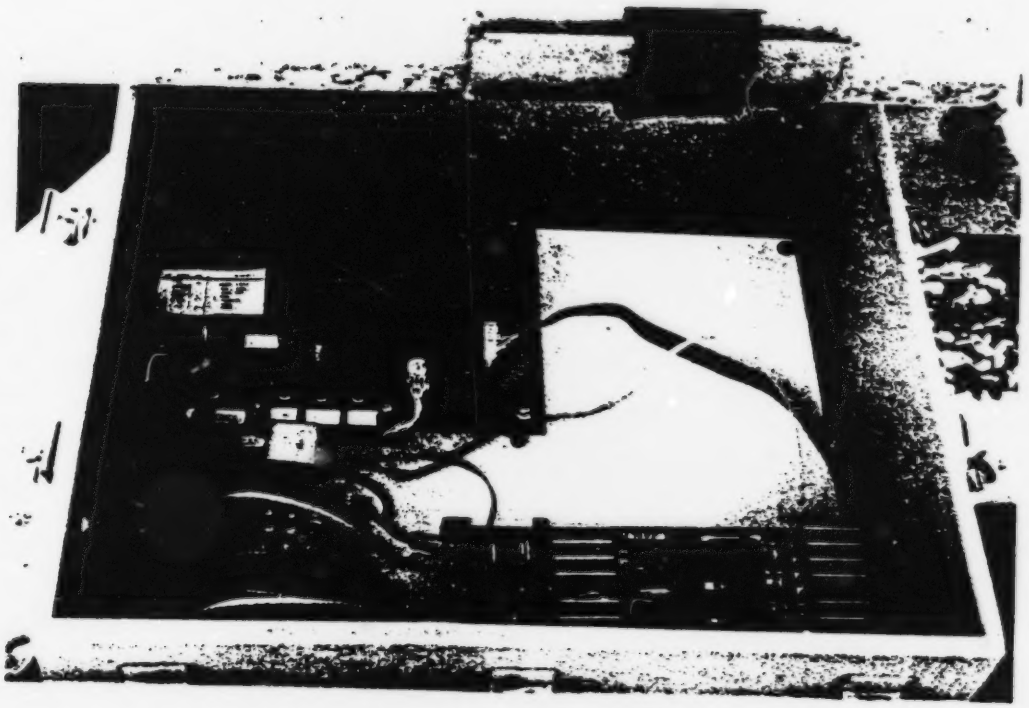


Figure 7: Photograph of the inside of the Mark I controller. The load-shedding circuitry is in the lower left quadrant and, just below it, obscured by the front side of the enclosure, is the main terminal strip connector.

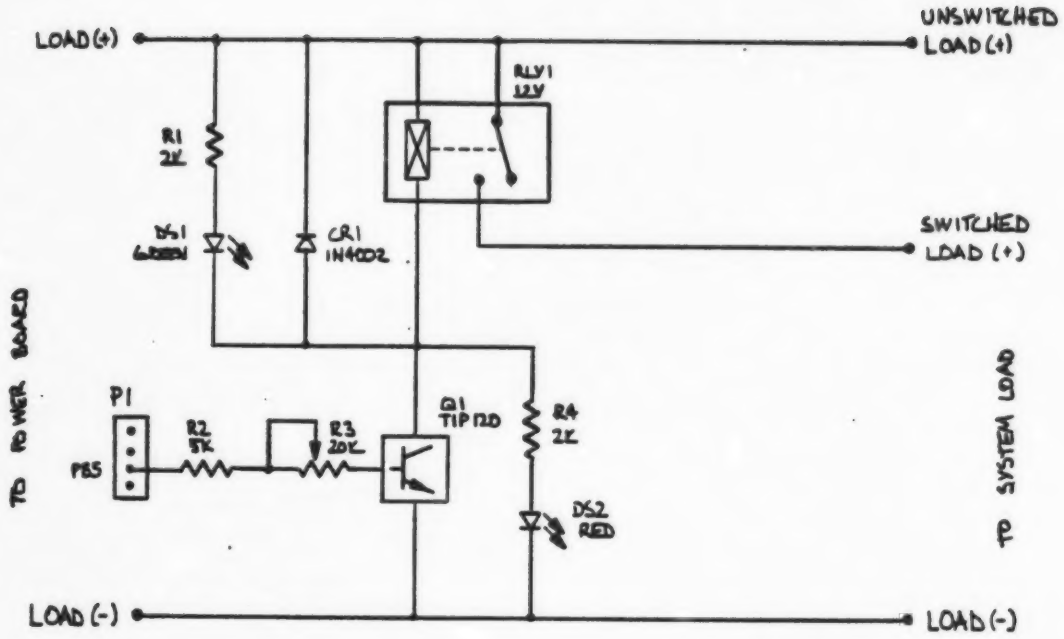


Figure 8: Schematic of the load-shedding circuitry.

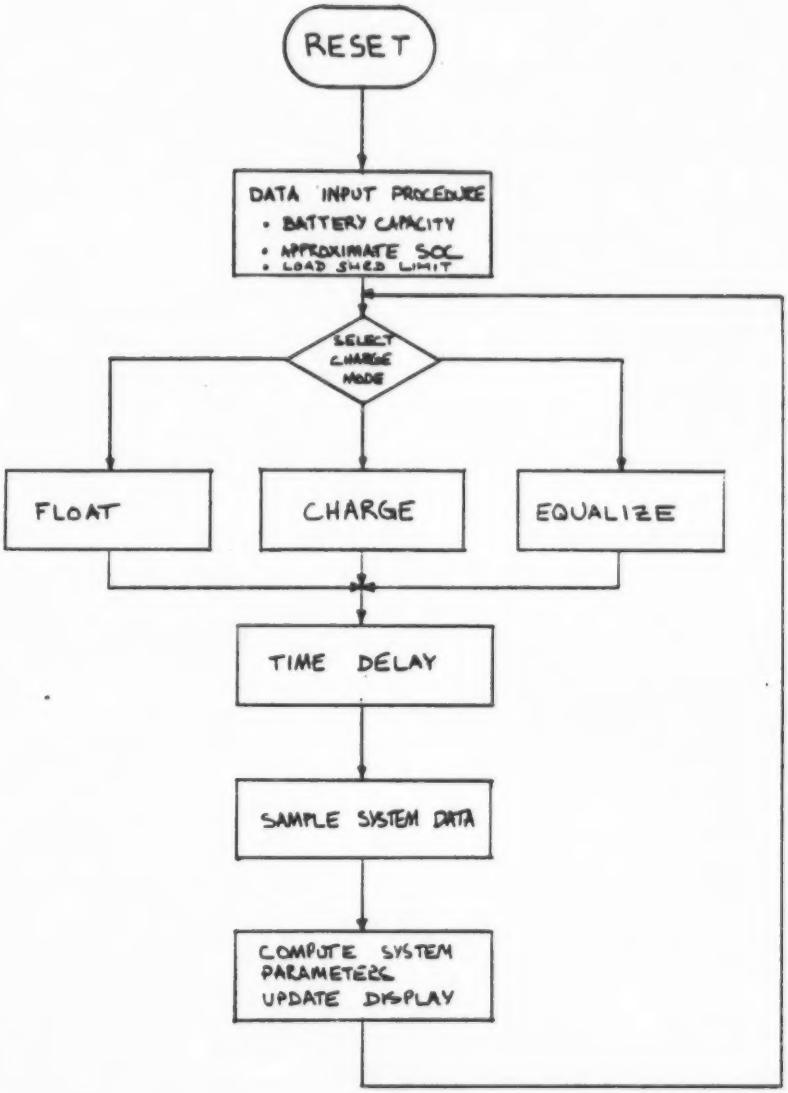


Figure 9: Program flow chart.

is represented in sign and magnitude by an 11-bit number.e.g. -1024 = 40A discharge, and +1024 = 40A charge; the current resolution is 39mA for the 0-10A range and 157mA for the 10-40A range. The charge flow in and out of the battery is approximated by a "summation of rectangles" theorem, yielding a charge resolution of 11.1 microamp-hr for the 0-10A range and 44.4 microamp-hr for the 10-40A range. The maximum allowed battery capacity is 2048 A-hr, corresponding to a 26-bit number representation.

Also included in the software is a battery overvoltage shutdown subroutine. This feature is activated only if the battery overcharges due to controller estimation error. This event is deemed to occur if the voltage reaches a preset limit (presently 17.5V). The remedial action is a forcing of the controller into the FLOAT mode, in which the voltage is clamped at 14V, so preventing battery damage or excessive water loss.

3.1.4 *Start-up procedure*

Start-up or reset of the controller is accomplished by depressing the switches on the logic board which are labelled: UP, DOWN, NEXT and RESET. The procedure is as follows:

1. Press RESET: display shows AAAA.
2. Press UP or DOWN switches: display shows battery capacity plus or minus 1 Ah, depending on which switch was pressed. Default value is 100 Ah.
3. Enter desired battery capacity via UP/DOWN switches: display shows battery capacity.
4. Press NEXT: display shows bbbb.
5. Press UP or DOWN switches: display shows state-of-charge plus or

minus 1%, depending on the switch pressed. Default value is 75%.

6. Enter desired SOC via UP/DOWN switches: display shows %SOC.
7. Press NEXT: display shows CCCC.
8. Press UP or DOWN switches: display shows the state-of-charge at which the load-shedding relay activates, plus or minus 1% according to which switch was pressed. Default value is 50%.
9. Press NEXT: display reads CXXX, where XXX is the %SOC.

After completion of this procedure the controller is operational. The various diagnostic functions listed in Table 1 can be displayed at any time by depressing the switch combinations indicated.

3.2 Evaluation Procedures

3.2.1 *Controller verification*

Verification of the correct operation of the controller can be achieved by performing the tests listed below. The tests are conducted with the battery disconnected, with a DC power supply acting in lieu of the array and with a rheostat as the load. Thus, the statement "supply a positive charge", which is used below, refers to application of a charging current to the terminals marked ARRAY. The statement "supply a negative charge" is actualized by setting the load resistor such that there is a discharge current.

1-9. As per start-up sequence.

10. Supply positive charge flow from external power supply: display should show increase of SOC.

11. Supply negative charge flow: display should show decrease of SOC.
12. Supply positive charge flow until SOC=100: display should read E100, indicating successful switching to EQUALIZE mode.
13. Supply negative charge flow: display should indicate return to CHARGE mode.
14. Supply positive charge flow to change mode first to EQUALIZE and then to FLOAT: display should read F100 and the red LED on the power board should extinguish.
15. Further positive charge should cause no change in display (trickle charging).
16. Supply negative charge flow of 1/2 Ah: display and power board LED should indicate a return to the CHARGE mode.
17. Supply negative charge flow until SOC=X, where X is the load-shed limit set during step 8: the load should disconnect. This action should be accompanied by a switching-off of the green LED on the relay subcircuit board, and a turning-on of the red LED on this board.
18. Supply positive charge flow until SOC>X: the load should reconnect and the LEDs on the relay board should change state.
19. Supply a voltage in excess of 17.5V to the terminals marked BAT: the display should indicate FLOAT mode. A return to the previous mode should be indicated 10 seconds after the voltage is reduced below 17.5V.

3.2.2 *Controller calibration*

Calibration of the current sensing circuitry of the controller was carried out using a 0-10A bipolar power supply, a precision ammeter in the

battery circuit, and a rheostat load. The actual current was set by the power supply, recorded by the ammeter, and compared to the current indicated by the controller's LCD (see Table 1 for appropriate switch settings).

Calibration of the charge counters was carried out by comparing the SOC indicated by the controller with the actual amount of charging/discharging, as computed from careful measurements of the duration of the current supplied/withdrawn.

3.2.3 *Field trials*

Field trials were conducted over the 5 month period, November 1986-March 1987, at BC Hydro's R&D facility in Surrey, BC. The controller was located on the roof, open to the elements, and was supplied by photovoltaic power from 10 ARCO 16-2000 panels connected in parallel, see Figures 10 and 11. This configuration of panels can supply a maximum current of 22A, at a voltage of around 15V. Thus it was ideal for the purposes of testing the controller in its "Mark I" state with a single power board. Both the logic board and the power board circuitry in Mark I were mounted on vector boards. The battery used in the trials was a brand-new 105Ah, deep discharge battery from C&B Batteries of Vancouver. The loads employed were fixed value resistors.

The battery was fully-charged at the commencement of the trial period. In November a resistive load of 110 ohms was used. This light load helped to simulate conditions appropriate to the late summer period of operation of a real system, i.e. when the battery is in near full charge condition, prior to meeting the demands of winter. There was no need to simulate winter conditions as these existed in reality over the period December-March. The weather provided a range of temperatures (about -10C to +10C) and a mixture of snow, rain and sunshine. The load during this period was 10 ohms. This "heavy" load induced a daily

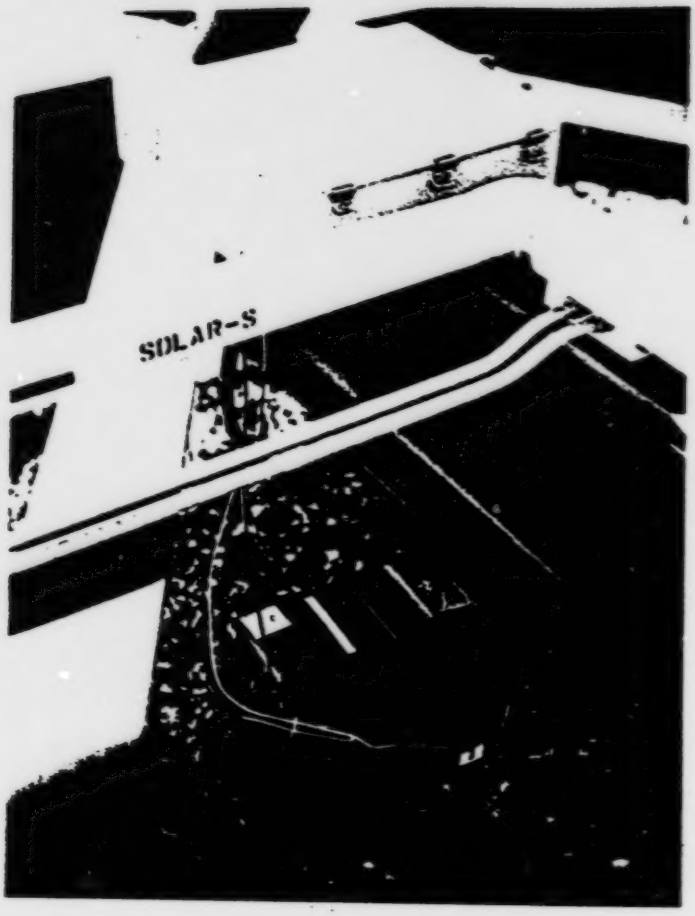


Figure 10: Photograph of the controller and battery at the BC Hydro test site.

Figure 11: Photograph of the 1kW PV array at the BC Hydro test site. The 10 panels on the right were used for the field trials. The PV array is mounted at the top of a field of solar thermal panels.

discharge of about 30Ah on sunless days. The test was rather severe as the battery was deeply discharged several times a month, rather than just once in a season as in a real system. The load-shed relay was set to activate at a SOC of 50Ah during these tests, and so the battery was well-protected against over-discharging.

In the final month (April 1987) of field trials the controller was located on the roof at Pulfrey Solar Inc. in Vancouver. A DC power supply was used in lieu of a PV array and was switched by a domestic timer. Two timing sequences, representing summer and winter were used, see Figure 12. The resistive load was also switched, via a relay, and two different duty cycles were used, see Figure 12. The objective of these trials was not only to test the efficacy of the controller under different load patterns, but also to make a comparison between the SOC displayed by the controller, and the SOC estimated from the more traditional measurements of electrolyte specific gravity and battery terminal voltage.

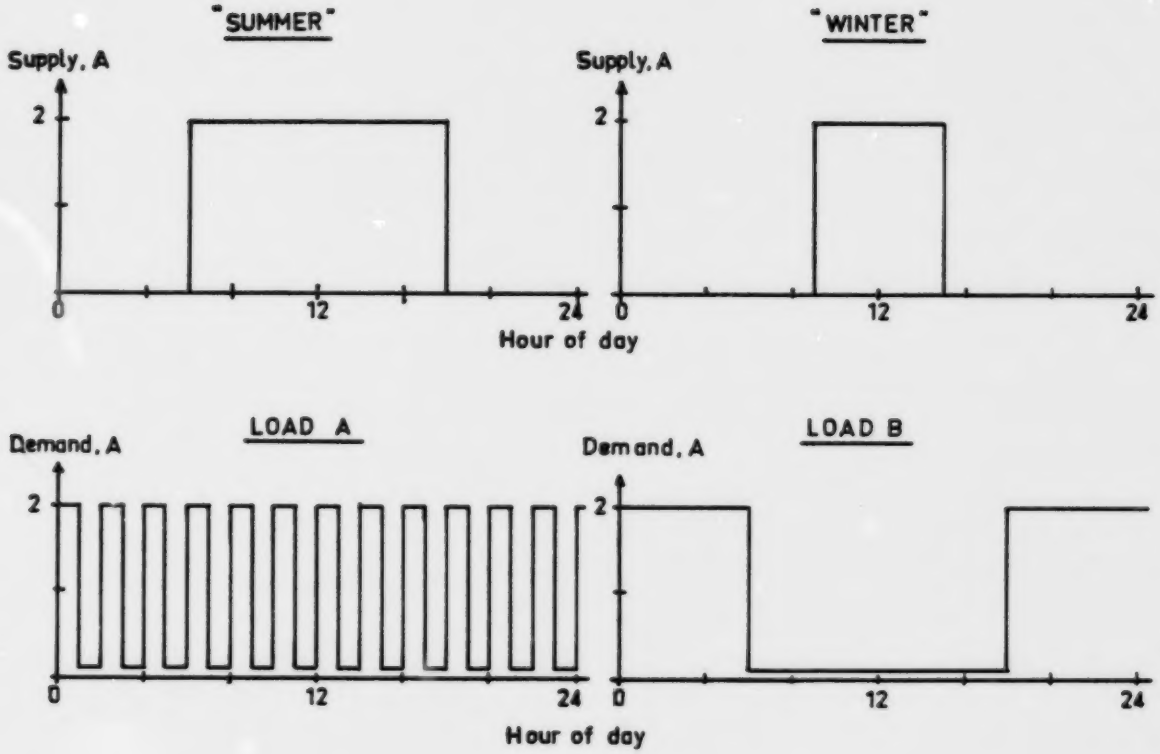


Figure 12: The power supply and load demand duty cycle patterns used in the field trials at Pulfrey Solar.

4.0 RESULTS AND DISCUSSION

4.1 Controller accuracy

The calibration tests, described in section 3.2.2, yielded the results shown in Table 2. The linearity of the current sensing circuitry is excellent. At all current levels tested, the displayed current is within 2 bits (80mA for the 0-10A range and 320 mA for the 10-40A range) of the actual current. A similar accuracy obtains for the SOC measurements, but the LCD displays only 3 digits so Figures 13 and 14 can only be expected to show agreement of actual and indicated SOC to within 1Ah. This measure of agreement was obtained.

4.2 Controller reliability

The prime purpose of the field trials, described in section 3.2.3, was to assess the reliability of the controller. The trials revealed only one problem, namely: a faulty EPROM. This device, the first EPROM tried in the controller, turned out to be physically defective in that it malfunctioned at temperatures below about 0C. The specified low temperature limit of the NMC27C16Q-35 is -10C. When this fault was detected and the EPROM replaced with a new device, there were no further troubles of any kind with the controller.

4.3 SOC Estimation

To carry-out the SOC comparison tests, described in section 3.2.2, it was

TABLE 2: Controller Current Calibration

CHARGE		DISCHARGE	
Actual I, A	Measured I, A	Actual I, A	Measured I, A
0.00	0.00	0.00	0.00
1.00	0.98	1.00	1.02
2.00	1.96	2.00	2.04
3.00	2.94	3.00	3.02
4.00	3.92	4.00	4.00
5.00	4.94	5.00	5.02
6.00	5.96	6.00	6.00
7.00	6.98	7.00	7.02
8.00	7.96	8.00	8.04
9.00	8.98	9.00	9.06
10.00	10.04	10.00	10.04

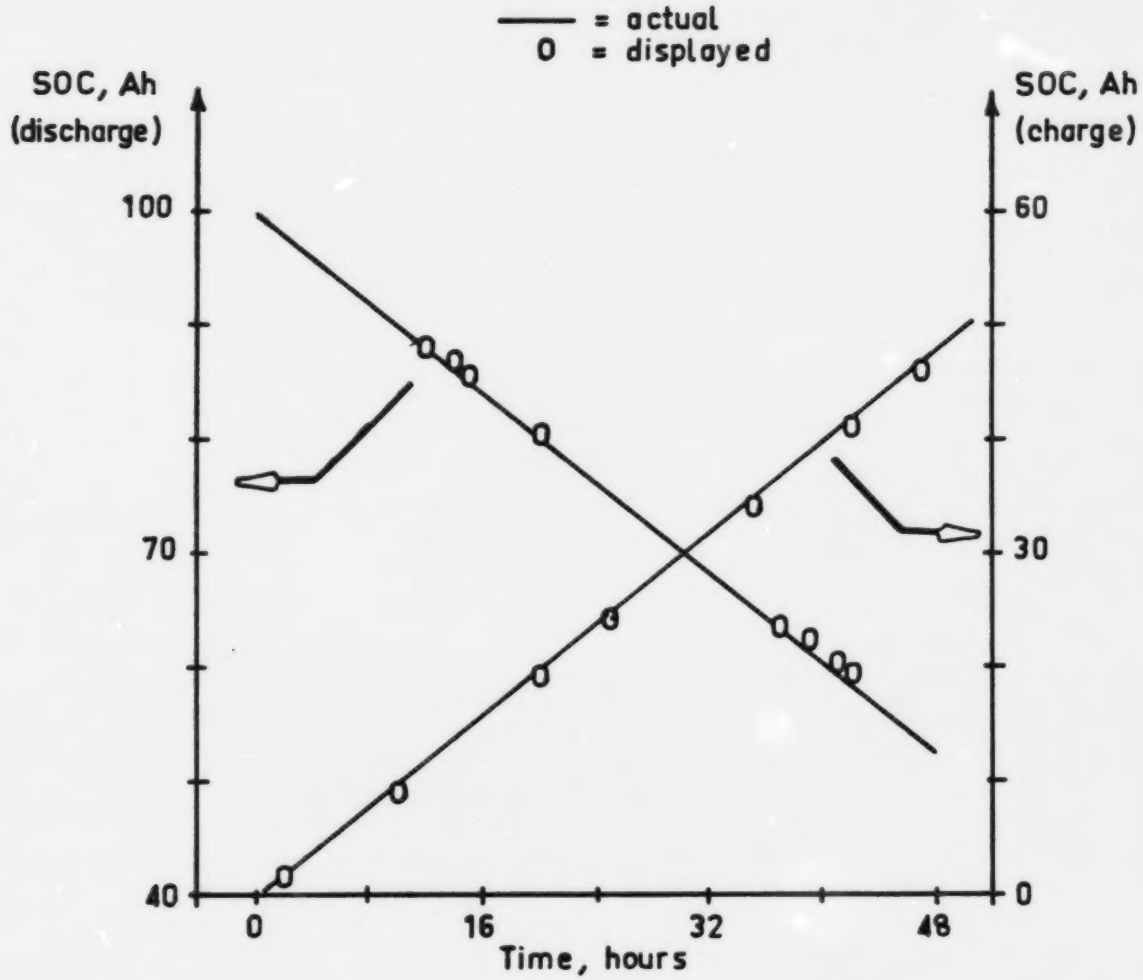


Figure 13: Charge and discharge characteristics at a fixed current of magnitude 1A.

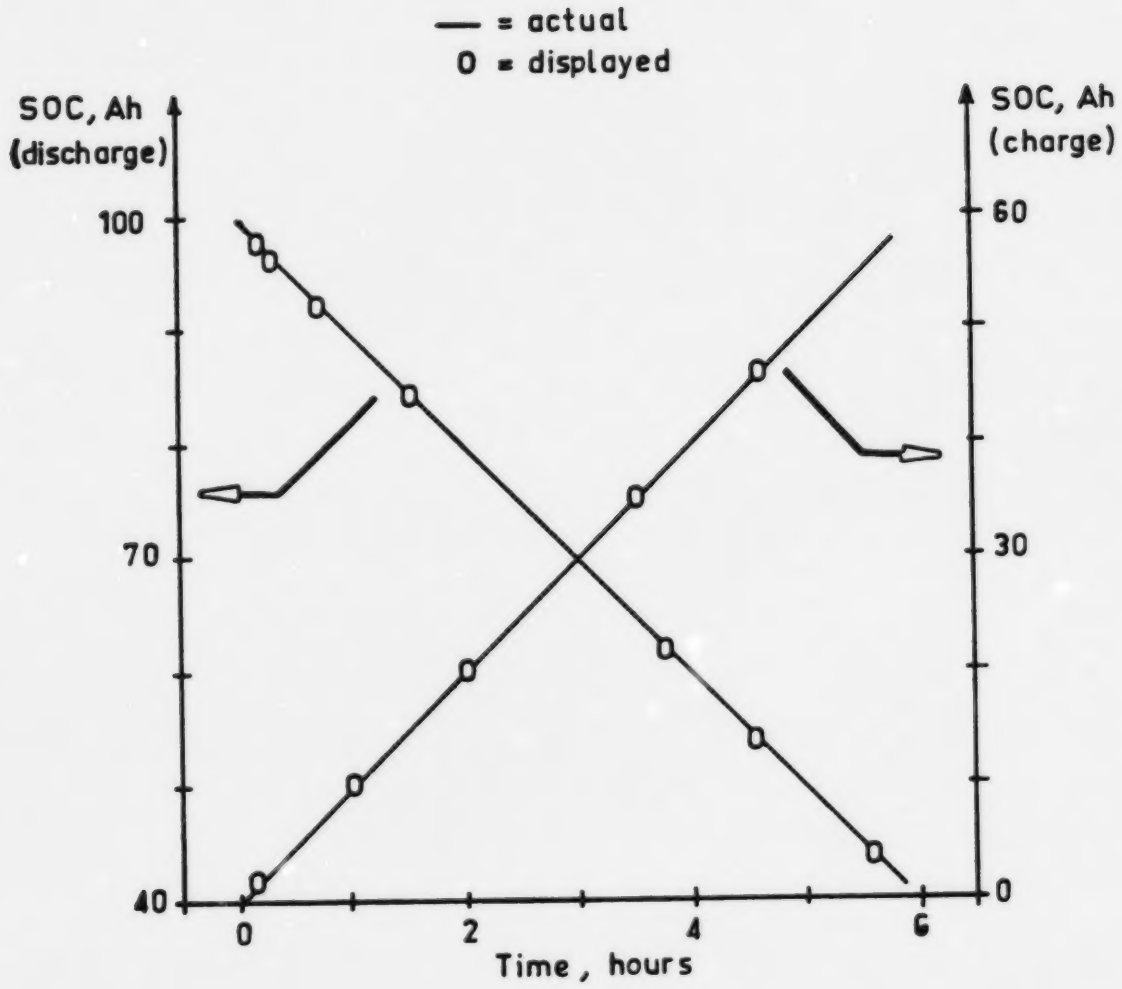


Figure 14: Charge and discharge characteristics at a fixed current of magnitude 10A.

first necessary to obtain calibration curves for the specific gravity and the terminal voltage. These were obtained by measurements taken at various times during the discharge, and the subsequent recharge, of the battery. The magnitude of the discharge and charge currents was 5A, and the currents were interrupted for several minutes to take the readings. The battery terminal voltage was measured with a precision voltmeter and the electrolyte specific gravity was measured with a temperature-compensated hydrometer. The results are shown in Figures 15 and 16. The non-linearity and the hysteresis of the curves illustrates the drawback to using either the teminal voltage or the specific gravity as a reliable estimate of SOC. The hysteresis in the specific gravity case, for example, comes about because, on charging, the newly-formed sulphuric acid sinks to the bottom of the battery. Thus, a hydrometer measurement which samples only the electrolyte at the top of the cells, gives an erroneously low reading. It is only during equalization, when the slight overcharge heats up the electrolyte and causes mixing of the acid and water, that a true reading of specific gravity is obtained. For our purposes, the calibration curves for specific gravity and terminal voltage were obtained by taking, in each case, the mean of the SOC values indicated for the discharge and charge conditions.

The comparison of SOC estimation via the three methods of specific gravity measurement, terminal voltage measurement and controller SOC computation, as described in section 3.2.2, yielded the results shown in Figures 17 and 18. For the 4 combinations of "season" and load examined, the SOC as displayed by the controller matches the actual SOC, as computed from current and time measurements, to within the resolution of the LCD, i.e. 1Ah. The estimates from the specific gravity and terminal voltage measurements are, as would be expected from the discussion of the preceding paragraph, not so accurate or uniform.

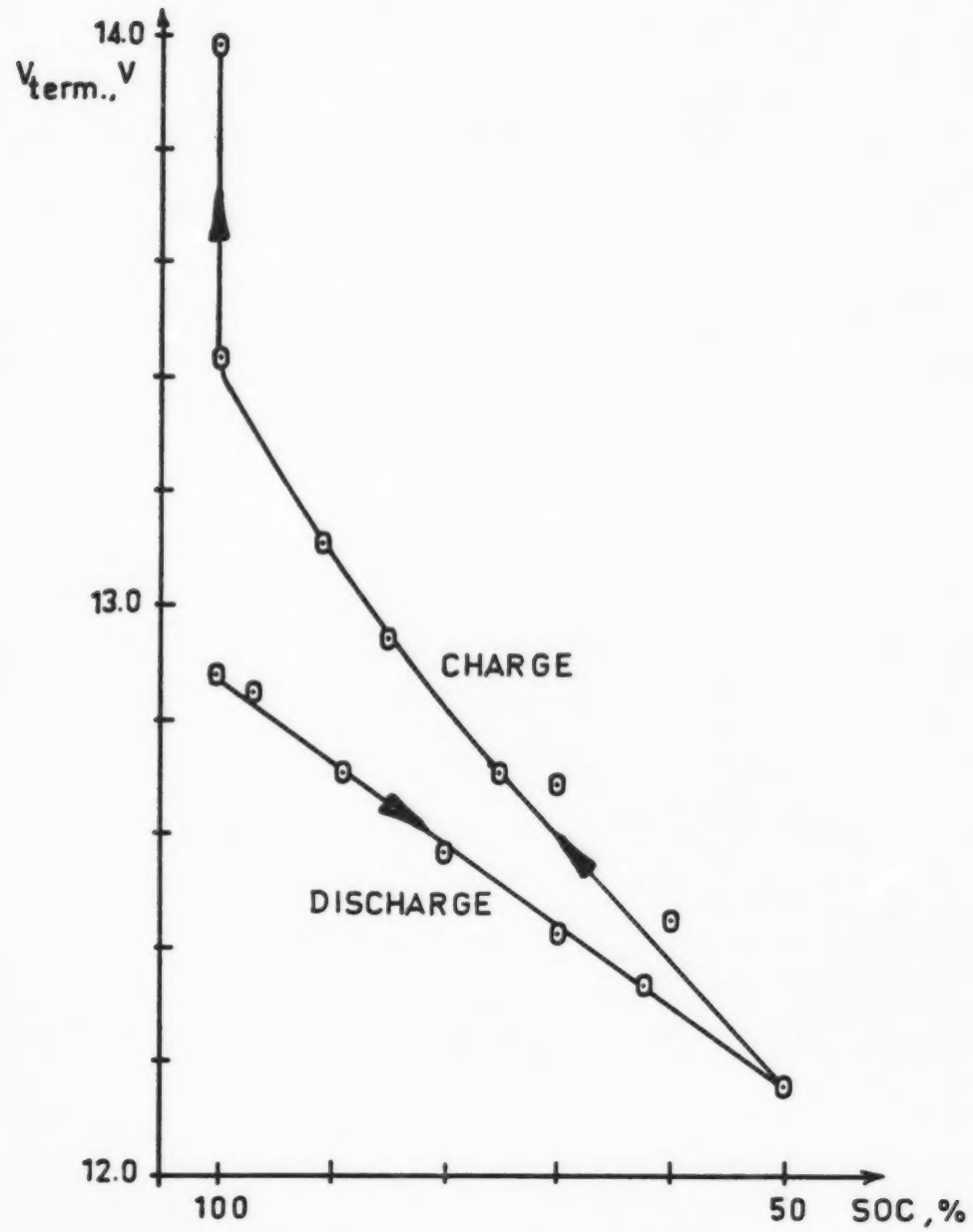


Figure 15: Variation of the battery terminal voltage with SOC during discharge, and subsequent recharge, at a fixed current of magnitude 5A.

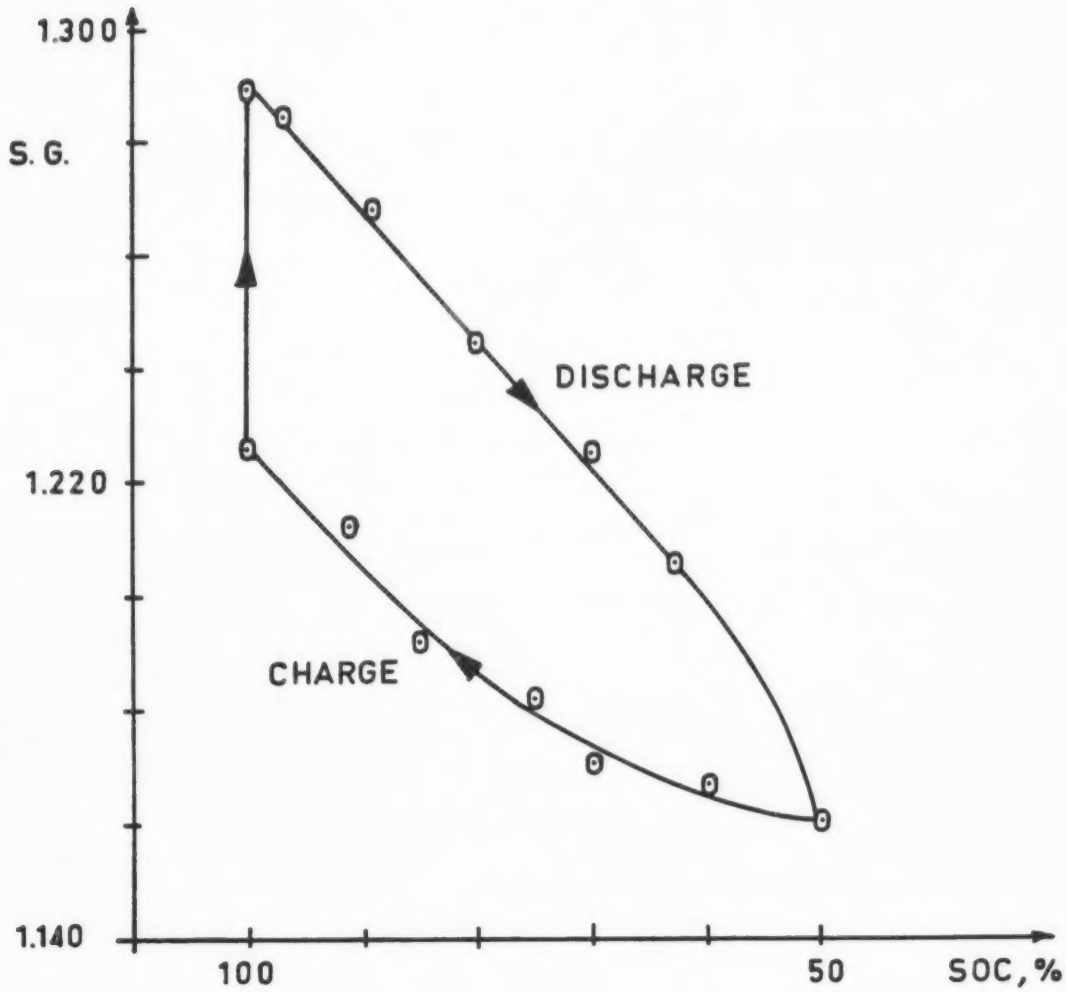


Figure 16: Variation of the electrolyte specific gravity with SOC during discharge, and susequent recharge, at a fixed current of 5A.

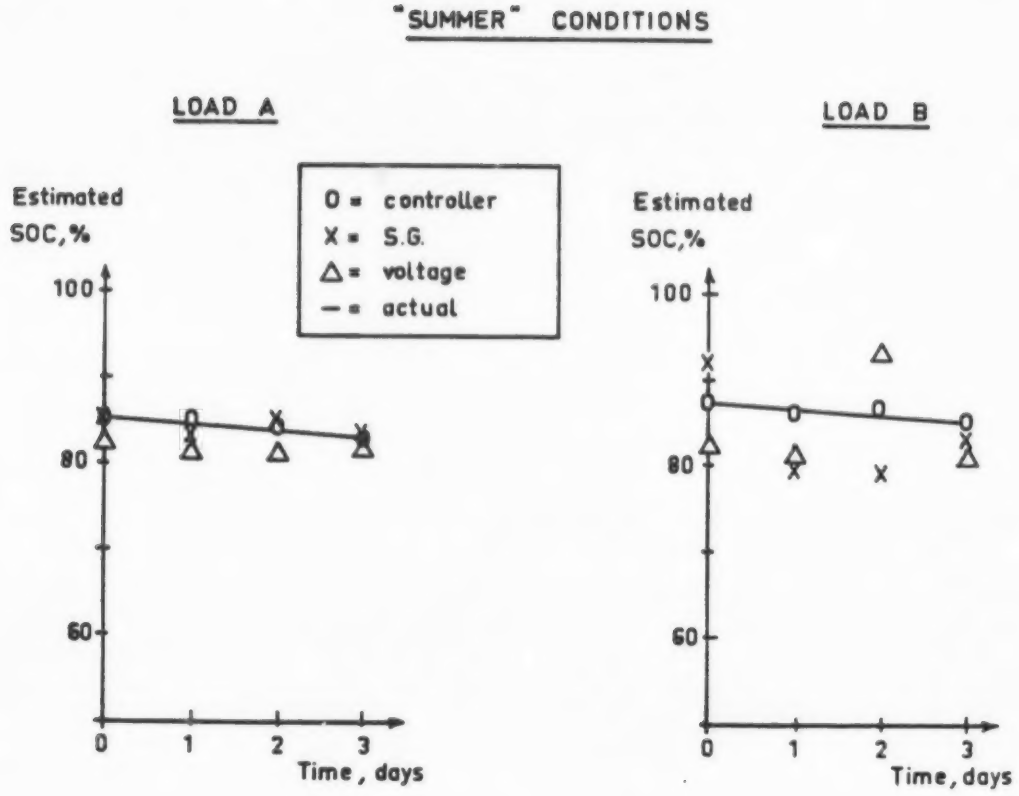


Figure 17: Comparison of three methods of estimating SOC under "summer" conditions.

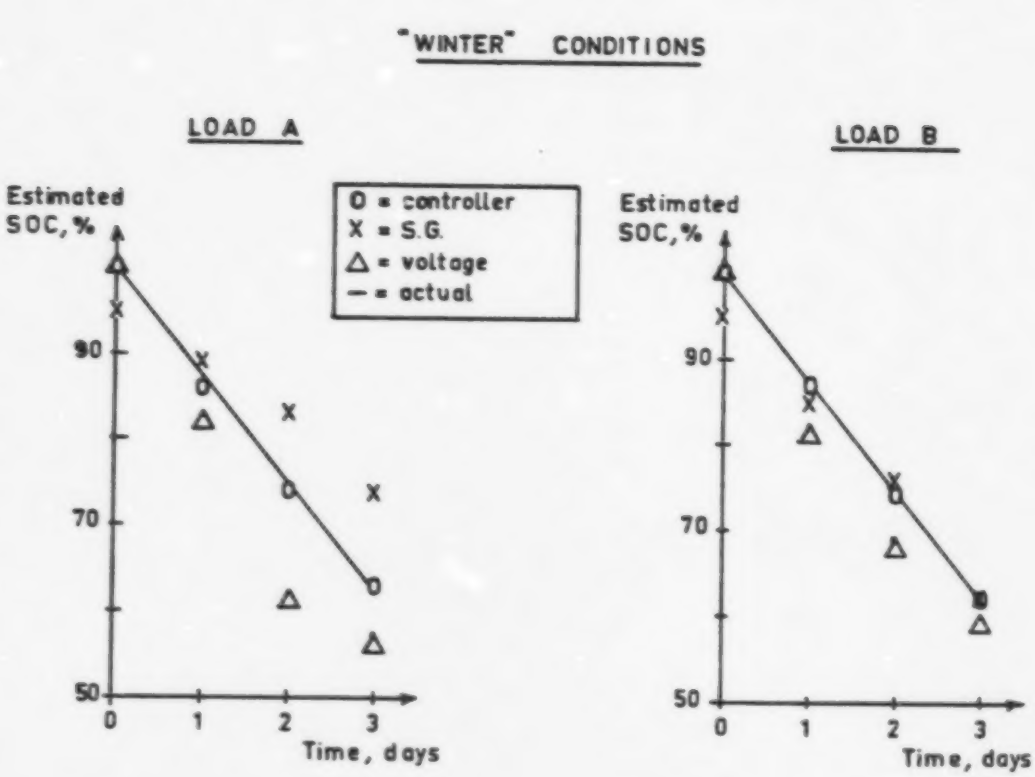


Figure 18: Comparison of three methods of estimating SOC under "winter" conditions.

4.4 Controller Cost

The cost of the electronic components for the Mark I 20A version of the prototype controller, including the terminal strip and load-shedding subcircuit, was $159. The additional cost of components for 3 power boards to make an 80A controller was about $200. Thus, the cost of components for a 40A controller, which would have a rating of 500Wp, would be about $225. The repeat-run costs to etch circuit boards for such a controller would be about $30. The remaining material cost would be in the enclosure. The off-the-shelf NEMA enclosure used in the prototype is able to accommodate the 5 boards of an 80A controller, with room to spare for the load-shedding circuitry and a very heavy duty terminal strip. However, its cost of $165 is clearly prohibitive for a production version of the controller. A reasonable estimate for large quantity, custom manufacture of an enclosure for a 40A controller might be about $40.

Adding-up the above costs we arrive at an estimated parts cost of about $295. Adding to this a figure of $50 for assembly and 10% for profit, yields an OEM selling price of about $380. This rough estimate indicates that the target figure for a 40A controller of $400, as suggested in section 3.1.1, may be attainable.

4.5 The Mark II Deliverable

The unit supplied to EMR as the contract deliverable was the Mark II version of the controller. It is rated at 80A and contained within the NEMA enclosure used for the field trials of the Mark I controller. The four power boards are mounted vertically, whereas the logic board's horizontal mounting makes for convenient viewing of the LCD and actuation of the switches. The unit

was supplied complete with load-shedding relays and a heavy-duty terminal strip.

Note that the controller can be used "as is" in applications where the maximum current is much lower than 80A. However, it is undesirable to do so because of the under-utilization of the hardware, and the slight loss of accuracy which arises due to the inverse relation of the resolution of the current metering system with the number of power boards employed, see Appendix 2.

4.6 Low Temperature Operation

The Mark I and Mark II controllers used standard CMOS ICs with low temperature ratings of around -10C. Extended temperature range versions of the chips are available, and it may be wise to use them for applications in the Canadian North. This would allow operation down to -40C.

Besides the integrated circuits, the switching and load-shedding relays also could be susceptible to malfunction at low temperatures. We have guarded against any such problems by employing, in Mark II, Potter and Brumfield T90 series, 30A relays. These units have silver-cadmium oxide contacts, an electrical life expectancy of 100,000 operations at rated load, and an operating temperature range of -55C to +85C.

5.0 CONCLUSIONS

The conclusions which can be drawn from the work described in this project are:

(i) battery state-of-charge estimation by charge integration using a

microprocessor-based battery charge controller is very accurate, considerably more so than the traditional estimation methods based on the specific gravity of the electrolyte and the terminal voltage of the battery.

(ii) a modular approach to controller construction, in which the circuitry is partitioned into 1 logic board and a number of power boards, depending on the desired rating, is both feasible and convenient.

(iii) the accuracy and reliability of the prototype controller is excellent.

(iv) an OEM selling price of around $400 for a 40A (500Wp) controller is realistic.

On the basis of these conclusions, the project can be judged to have been an unqualified success. The objective of the project has been met, namely: the practicability of a modular charge controller, based on the charge integration method of state-of-charge estimation, and capable of servicing medium-size PV systems (250-1000W), has been demonstrated.

6.0 RECOMMENDATIONS

(i) The success of the project encourages us to recommend that plans for manufacturing and marketing the controller commence immediately. The first step in this direction should be the seeking of a manufacturer and supplier of custom enclosures for the various sizes (20, 40, 60 and 80A) of the controller.

(ii) Before production-scale manufacture begins it is recommended that field trials of the Mark II 80A version of the controller be carried-out at "real" sites.

(iii) As some applications of the controller may be in the Canadian North, it is recommended that a low temperature version of the controller (see section 4.6) be built and field-tested.

APPENDIX 1

LITERATURE ON RELATED PRODUCTS:

- The Solar Sentry from BOSS
- The PBR series from SunAmp Systems Inc.
- The MAC from Trisolar.

BOSS
BALANCE OF SYSTEMS SPECIALISTS, INC.
7745 EAST REDFIELD ROAD SCOTTSDALE, ARIZONA 85260

INSTALLATION INSTRUCTIONS

FOR THE

SOLAR SENTRY

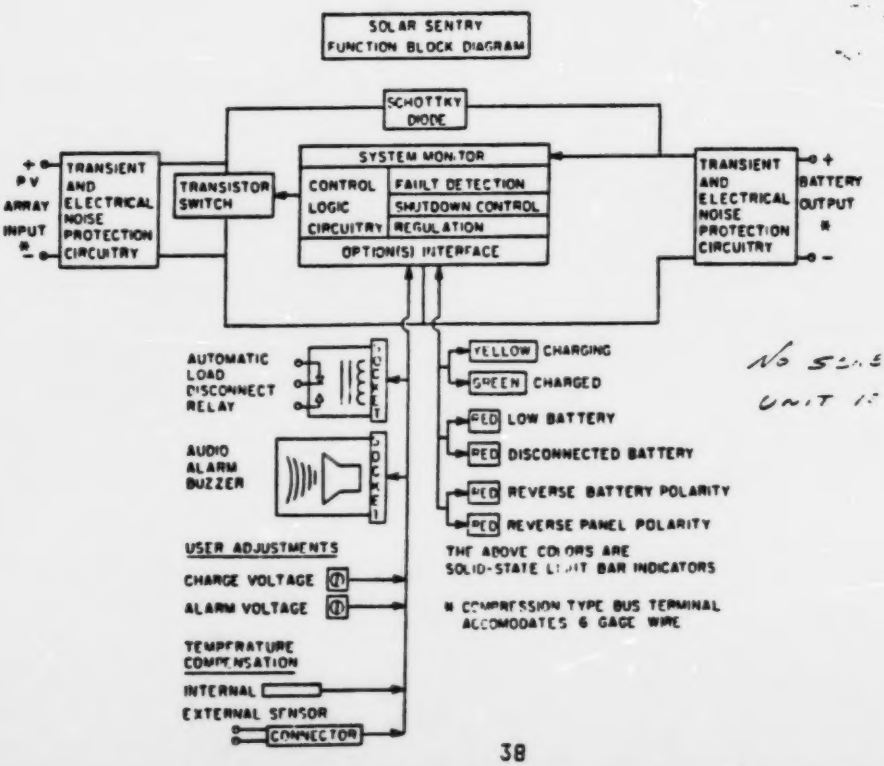
PHOTOVOLTAIC SYSTEM BATTERY CHARGE CONTROL REGULATOR

The SOLAR SENTRY is a 100% solid state voltage regulator that features continuous automatic system control. This document includes the Theory of peration, Installation Instructions, Data Sheet and Warranty. It is important .hat the Theory of Operation and the Installation Instructions are fully understood before installing the controller to ensure proper and safe system peration.

BATTERY STATE-OF-CHARGE CONTROL THEORY OF OPERATION

SOLAR SENTRY Regulators control battery state-of-charge (SOC) by electrically controlling the systems PV array power generating capability. When SOC is less than 100%, circuitry in the SOLAR SENTRY permits the PV array to enerate and deliver electrical charging current to the battery. When the attery recharges fully to 100% SOC, the SOLAR SENTRY circuitry stops further charging action by electrically halting the PV arrays capability to deliver harging current. This is accomplished by utilizing transistors to safely hort-circuit the array.

SOLAR SENTRY's are switching shunt type regulators. Solid-state nsistors act as switches which force the PV array into short-circuit mode operation upon detection of 100% SOC. This causes the PV array voltage to drop towards zero, thereby ceasing further delivery of charging current. In this anner, PV array power is dissipated in the array's internal resistance and not n the regulator.



Regulation of battery SOC is achieved by monitoring battery voltage to ·ermine whether additional charging is required. Control circuitry c. tinually monitors battery voltage to detect any change in battery SOC, and initiates further charging action whenever necessary.

Temperature compensation of battery charge voltage is available in two options, either as internal circuitry or as an external sensor. Internal emperature compensation requires the SOLAR SENTRY to be in close physical roximity to the battery(s). The external sensor option allows the SOLAR SENTRY to be located away from the battery: the sensor sends temperature information o the SOLAR SENTRY through an electrical cable.

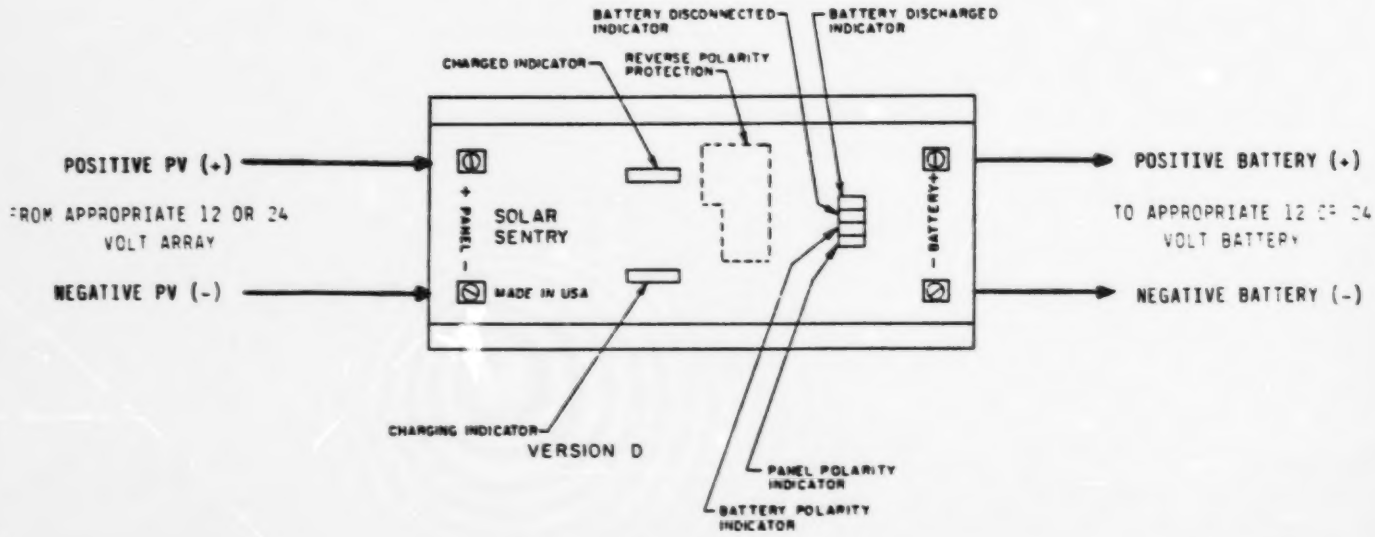
NOTES:

ocation and Mounting: Do not install regulators with the relay options inside a non-vented battery enclosure. When storage batteries are being charged they emit a highly explosive gas that may be ignited with relay contact arcing. ount indoors (Version A may be mounted outdoors) in a location that will allow he heat from the regulator to escape and provide cool operation. Be sure that the regulator is securely fastened to the wall to prevent the tension of the ires from pulling it down.

ystem Wiring Procedure:

NOTE: BEFORE ATTACHING ANY CABLES TO THE SOLAR SENTRY IT IS NECESSARY TO ERVE ALL POLARITIES TO PREVENT ARCING AND DAMAGE TO SYSTEM COMPONENTS.

A wiring schematic has been provided to help clarify the connection rocedure. Before the starting of the installation it is recommended that the ace of the solar modules be covered to prevent their generation of electricity. Also the SOLAR SENTRY-to-battery cables should be connected at the regulator first, and next at the battery to avoid arcing.



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STEP	CONNECTION
1	Battery Negative (-) Cable to SOLAR SENTRY Battery (-) Terminal
2	Battery Positive (+) Cable to SOLAR SENTRY Battery (+) Terminal
3	Array Negative (-) Cable to SOLAR SENTRY Panel (-) Terminal
4	Array Positive (+) Cable to SOLAR SENTRY Panel (+) Terminal
5	Uncover Solar Modules

CHECK OUT PROCEDURE

. Measure battery voltage at the SOLAR SENTRY terminals with a voltmeter.
2. Measure array voltage at the SOLAR SENTRY terminals with a voltmeter.

If the array voltage is slightly higher (approximately 1/2 volt) than the battery voltage, the system is charging. This should be indicated by a brightly lit yellow light bar on SOLAR SENTRY Versions B, C or D. If the array voltage s very low (approximately 1 volt), then the regulator is in the full charge shunt mode) and the green light bar should be lit (on Verions B, C or D). If so, proceed to step 3. If the array voltage is slightly higher than the battery voltage, the installation procedure is complete.

3. NOTE: This procedure requires the photovoltaic array be energized by sunlight. The following steps should therefore be performed during the daytime nd not at night.

To ensure that the regulator's circuitry is immediately reset properly, mentarily disconnect the battery positive terminal wire and then reconnect it. his will allow the photovoltaic array voltage to rise to it's maximum, which will trigger the regulator's circuitry to reset to the charge mode.

Step 3 is not mandatory, as the regulator's circuitry will automatically self-reset once the battery is discharged sufficiently to require charging. Momentary disconnection of the positive battery terminal wire simply causes this eset mechanism to occur immediately.

If, after performing step three, the green light bar is still lit (and the rray voltage is still low), the battery is fully charged and the regulator ircuitry is reset and is operating properly.

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SOLAR SENTRY SPECIFICATIONS

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
Array Current, nom	Charging Current @ max power (Imp) 10 Amp Version		10		Amperes
Array Current, nom	Charging Current @ max power (Imp) 20 Amp Version		20		Amperes
rray Current, max	Short Circuit Current (Isc) of Array, 10 Amp Version	11	11.5	12.0	Amperes
Array Current, max	Short Circuit Current (Isc) of Array, 20 Amp Version	22	22.5	23.0	Amperes
Array Voltage, max	Open Circuit Array Voltage, 12 Volt Version		20	22	Volts
rray Voltage, max	Open Circuit Array Voltage, 24 Volt Version		40	44	Volts
attery Charged Voltage (1)	Charge Termination Voltage @ 25 Degrees C (77 Degrees F), LA	14.41	14.48	14.55	Volts
Battery Charged Voltage (1)	Charge Lead Calcium, LC	14.71	14.78	14.85	Volts
attery Charged Voltage (1)	Charge Delco 2000, DL	14.11	14.18	14.25	Volts
Battery Charged Voltage (1)	Charge Pure Lead, PL	14.31	14.38	14.45	Volts
Battery Charge Hysteresis	See Note 2	.72	.80	.84	Volts
Auto Shutdown Voltage	Battery Disconnected	16.7	17.0	17.5	Volts
Internal Voltage Drop	Voltage drop from PV(+) to Batt(+) Terminals at rated current	.50	.55	.65	Volts
Quiescent Current	Battery @ 14.4VDC, Version A	14	15	16	MA
Quiescent Current	Battery @ 14.4VDC, Version B	38	40	44	MA
uiescent Current	Battery @ 11.5VDC, Version C	26	28	30	MA
uiescent Current	Battery @ 11.5VDC, Version D	28	30	33	MA
Relay Current	Battery @ 11.5VDC	66	70	77	MA
uzzer Current	Battery @ 11.5VDC	37	39	42	MA
Low Battery Detect	Discharged Battery Voltage	11.45	11.50	11.53	Volts
ow Battery Hysteresis	See Note 3	1.7	1.8	1.9	Volts
Low Adj. Range Option	Low Battery Detect Adjustment When Calibrated to 11.0VDC	0.9	1.0	1.1	Volts
Lightning Protection	(4) 12 Volt Version 10 or 20 amp	10.00			Amps
ightning Protection	(5) 12 Volt Version 10 or 20 amp	5			Joules
ightning Protection	(6) 12 Volt Version 10 or 20 amp	53,000			Watts
Lightning Protection	(4) 24 Volt Version 10 or 20 amp	23			Amps
Lightning Protection	(5) 24 Volt Version 10 or 20 amp	1.5			Joules
ightning Protection	(6) 24 Volt Version 10 or 20 amp	1500			Watts

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
mbient Operating Temp Max	@ Max Array Current	50(122)			C(F)
Ambient Operating Temp Max		-20(-4)			C(F)
mbient Storage Temp Range		-20(-4)		50(122)	C(F)
emp Compensation, Slope (7)	5 C Ambient	-26	-28	-30	MV/ C
emp Accuracy	Over Temp Operating Range		0	1 2	%

MECHANICAL SPECIFICATIONS

imensions	LxWxH	10 Amp	8.0(20)x4.8(12.1)x1.3(3.2)	in(cm)
imensions	LxWxH	20 Amp	8.0(20)x4.5(11.4)x2.5(6.4)	in(cm)
eight	10 Amp		1.2(5.4)	lb(kg)
eight	20 Amp		1.8(.82)	lb(kg)

OTES:

1. Battery charged voltage is the voltage that the manufacturer recommends as representing the 100% State of Charge condition for a specific battery type, i.e. lead antimony, lead calcium, pure lead, or Delco 2000. All BOSS regulators are factory calibrated to those specific battery types as standard. Other calibrations available, contact factory.

2. Battery Charge Hysteresis is the amount of voltage a battery must be discharged before recharging begins.

3. Low Battery Hysteresis is the amount of voltage a battery must be recharged before the regulator re-energizes the system's electrical loads.

4. Electrical surge rating, in amperes, is that which the regulator is capable of absorbing without damage. Rating assumes multiple pulses of current of duration less than or equal to a standard (ANSI STD. C62.1) 8/20 microsecond waveshape.

5. Electrical surge rating, in joules of energy, is that which the regulator is capable of absorbing without damage. Rating assumes a single pulse of energy of duration less than or equal to a standard (ANSI STD. C62.1) 10/1000 waveshape.

6. Electrical surge rating, in watts of power, is that which the regulator is capable of absorbing without damage. Rating assumes multiple 8/20 microsecond surge pulses within a 1 millisecond time period.

7. 12V version, 24V version is double this value.

PERATION OF THIS PRODUCT ABOVE THE "MAXIMUM RATINGS" MAY CAUSE PERMANENT DAMAGE T THE DEVICE. BALANCE OF SYSTEMS SPECIALISTS, INC. RESERVES THE RIGHT TO MAKE HANGES IN THE CIRCUITRY OR SPECIFICATIONS AT ANYTIME WITHOUT PRIOR NOTICE.

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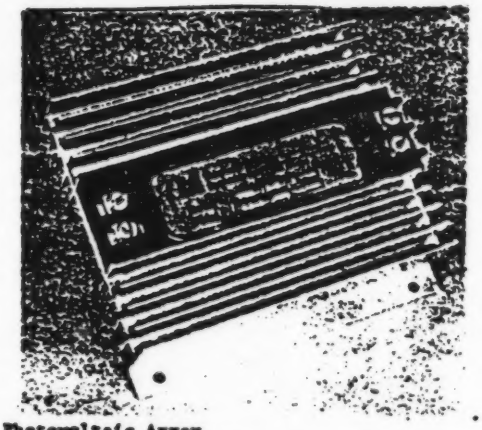
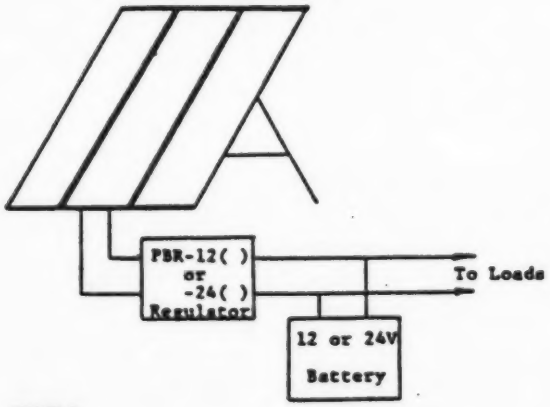
SunAmp Systems Inc.

PHOTOVOLTAIC PRODUCTS

12 AND 24 VOLT PHOTOVOLTAIC CONTROLLERS



Photovoltaic Array
Up to 130 Watts peak at 12V
260 Watts peak at 24V



MODELS:

PBR-12(FL) and PBR-24(FL) For Pure Lead Batteries
PBR-12(LC) and PBR-24(LC) For Lead Calcium Batteries
PBR-12(LA) and PBR-24(LA) For Lead Antimony Batteries
PBT-12(NC) and PBR-24(NC) For NI-CAD Batteries

The PBR-12 and PBR-24 are highly reliable and efficient photovoltaic battery regulator systems using patented circuitry.

All solid state, with no moving parts, the units are low cost, yet very reliable.

The PBR-12 is excellent for recreation vehicles, sail boats and remote area applications where the total photovoltaic capacity does not exceed 130 watts peak.

ADVANTAGES

* Completely solid state. No mechanical relays to wear out
* Rugged construction assures high reliability
* 130 watt peak photovoltaic module capacity (260 watts for 24 volt system)
* Temperature compensated voltage regulation extends baytery life and reduces water loss
* Sufficient bubbling is allowed to prevent electrolyte "stratification"
* Automatic equalization of batteries by applying full charge current rather than trickle charging (preferred for long battery life)
* Lightning and transient protection reduces system failures. (Module mounting frame should still be grounded)
* Internal blocking diode prevents discharge of batteries through the modules at night
* Can handle "edge of cloud effect" currents up to two times specified current rating for short periods.
* Easy to install. Need only a screwdriver

OPERATING TEMPERATURE

* -40°C to 55°C

0384

MICROPROCESSOR CONTROL OF PHOTOVOLTAIC SYSTEMS

By Dr. Alan R. Millner
David L. Kaufman

TriSolarCorp
Bedford, MA USA

ABSTRACT

A new, low power CMOS microprocessor controller has been developed for photovoltaic power systems. Programs have been developed for three types of systems: conventional battery charging systems with state of charge estimation and sequential shedding of subarrays and loads; maximum power controlled battery charging systems; and, variable speed DC motor drives. While this equipment has been utilized for terrestrial applications, it could readily be adapted for spacecraft usage.

THE PROBLEM

Photovoltaic systems need controls of varying scope depending on the system size and application. While low cost voltage regulators are adequate and available for small battery chargers, many larger or more complex systems require control algorithms which until now could only be achieved by costly custom engineered products. The problem is made more difficult because the modular nature of photovoltaic systems results in a great variety of controller requirements.

THE SOLUTION

Under the sponsorship of the US Department of Energy, with technical management by NASA Lewis Research Center, TriSolarCorp has designed, built and tested a microprocessor automatic controller (MAC) to fill this need. The MAC will charge batteries from 12 to 300 volts or will operate motors without batteries up to 180 volts DC. The controller requires less than 5 watts and can draw power either from the system it controls or from a separate 12 volt battery.

The first unit was produced and tested for NASA at TriSolarCorp. This unit is shown in Figure 1. It is a 5kW maximum power controlling battery charger also configured as a 5kW batteryless motor drive.

This work was performed under U.S. Dept. of Energy, Div. of Photovoltaic Energy Systems.

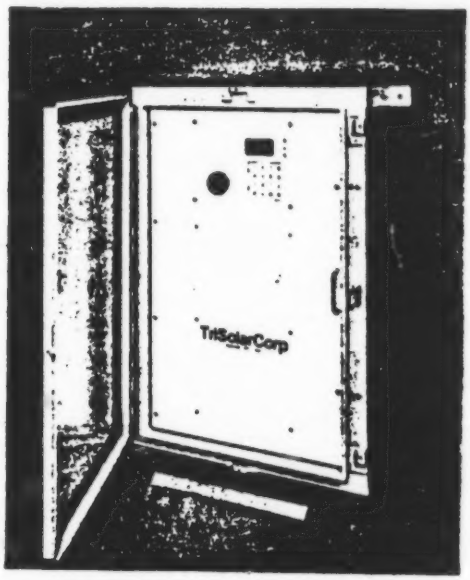


Fig. 1 Microprocessor Controller

The entire controller interfaces with existing 500 watt TriSolarCorp power modules, operates in a NEMA-4 enclosure over an ambient temperature range of -25 degree C to +45 degrees C, operates from either a 12V battery or a 40V to 300V DC unregulated solar array or battery bus.

HARDWARE DESCRIPTION

The prototype microprocessor PV system controller consists of a NEMA-4 enclosure containing the following major electronic assemblies:

A. Power Supply
B. Display and Control Interface
C. Resistor Divider Board
D. Power Modules (10)
E. Processor

The power supply consists of a wide input range DC to DC down converter and a multi-output flyback DC to DC converter. The down converter accepts 40V to 300V DC.

CH2019-8/84/0000-1288 $1.00 © 1984 IEEE

The display and control interface consists of a 4 1/2 digit LCD display, a 16 key membrane switch pad (calculator style), an audible alarm, and three LED's: RED, YELLOW, and GREEN. The keypad allows manual control (under password security) of the system and calls up any one of over 50 different quantities to be displayed. The display normally shows battery state of charge but can display the voltage, current, or power of any array string, load bus, battery, motor, or other monitored point, monitored temperatures, or time of day. The LED's summarize system status: The GREEN LED shows that the processor is running and servicing timer interrupts. The RED LED indicates that the battery is dangerously low and loads have been shed, and the YELLOW LED indicates that stored energy is in short supply and should be conserved.

The resistor divider board serves as an interface between the high voltages in the power system and the low voltage signals measured by the processor. The power modules are 500 watt DC to DC converters used, for the prototype, to couple the 180 volt nominal solar array inputs to the 120 volt nominal battery and load bus. These are 20kHz switching type bucking converters, with typical efficiency of 98%. They include internal fast current limiting. Ten power modules are provided in the prototype.

The processor is a large board containing the following parts:

1. Central Processor: CPU, timer, ROM, R..
2. Analog input section: differential current multiplexer, single-ended voltage multiplexer, and 10 bit plus sign A/D converter
3. Display and control interface: UART for RS232 interface support; PIA for keypad, LED, LCD, and interrupt support; 6 opto-isolators for load control
4. Array control buffers: 10 digital outputs which can be used as pulse width modulated 20kHz signals for the power modules for maximum power point tracking, or can be used as switch drive signals for discrete array control.

The central processor is built around a 65C02 CPU, which operates at 1MHz with an 8 bit data bus and a 16 bit address bus. This addresses 16k bytes of CMOS EPROM and up to 6k bytes of CMOS RAM. (This program requires only 2k of RAM.) Address and data bus buffers separate the central portion of the processor from the rest of the controller. A multiple timer, the AM9513, is used to generate the 4MHz master crystal oscillator clock, 1MHz system clock, the time of day, the two pulse width modulated 20kHz outputs, the 16X baud rate clock for the RS232 port, and a 4msec interrupt used in the program. All "glue" chips (assorted small gates) are of the 74HC family for adequate speed at CMOS power levels. An address decoder for other major sections of the controller is also included in this section.

The heart of the analog input section is the AD7571 analog to digital converter. This new device is a CMOS low cost unit, with 10 bits plus sign accuracy, and internal interface to an 8 bit microprocessor bus.

The input to the converter comes from an analog multiplexer. This services inputs for 16 voltage sampling channels, 16 currents, two thermistor inputs, a 4V reference, a ground reference, and the current measurement differential multiplexer. Measured accuracy at room temperature through the A/D converter is +/-0.2%.

Anti-aliasing filter design of the current sense inputs is based upon the possibility of 100 or 120Hz square waves on the battery current line, sampled at the 4msec rate and averaged 16 times, resulting in an accuracy of +/-2%. This resulted in a 2 pole filter with poles at 5Hz and 51Hz.

The display and control interface consists of a 65SC21 peripheral interface adapter (PIA) and an octal latch driving optoisolators.

The PIA provides input/output ports which service the LCD display, the keyboard, and the signals for the LED's and audio alarm, and are inputs for the UART status flags. The interrupts provide for the 4msec timer and the panic shutdown switch functions as well as UART service.

The RS232 port is provided by an IM6402 CMOS UART, which with a few discrete driver elements, makes a complete bi-directional asynchronoeus communications interface. This port allows data logging to an external printer, automated testing during manufacture, or computer interfacing in special applications.

The array control functions consist of a set of latches, gates, and buffers allowing 12 digital outputs to be driven as independent relay drive signals for discrete array control, or as separately buffered pulse width modulated 20kHz signals for maximum power point tracking. A watchdog timer turns off the array control and load outputs if the processor fails to reset it within 240msec. An additional analog output, 0 to 10V, is available for continuous analog control of variable loads such as variable speed motor drives. This is realized by low pass filtering of a second PWM signal. Alternatively, the 12 array control outputs can be partitioned between the two PWM signals to provide max power tracking into two independent loads, although the present software doesn't yet fully support that mode of operation.

SOFTWARE DESCRIPTION

The software design was based on two decisions. First, the software is modular. This allows an orderly linking of software modules using the principles of structured programming and allows modules to be modified without interfering with the rest of the program. Second, the modules were defined using "pseudocode", an explicit definition of each algorithm in plain english with a program format. This allowed clear

communication between system designer, hardware designer, and software designer in advance of actual programming and eased the task of uniting assembly language code.

The MAC unit is designed to operate without any human intervention. It performs the following functions automatically:

1. Battery Control
2. Array Control
3. Load or auxiliary display on the control panel
4. Status display on the control panel
5. Self-test
6. Data logging via RS232C port

In addition, the MAC unit provides the following facilities for manual control:

1. Manual battery charge initialization
2. Manual array control
3. Manual load or auxiliary charger control
4. Control panel display of system operating parameters
5. Manual test calibration mode and time of day
6. Remote control and parameter measurement or automated testing via the RS232C port

Each function is described below, with the automatic and manual functions described together for ease of understanding.

Battery State of Charge

The state of charge describes the battery's condition at an instant in time. The state of charge of the battery is defined to be a percentage equal to 100 times the number of ampere-hours the battery can deliver at 25 degrees C at its specified rate, divided by the battery's rated ampere-hour capacity at 25 degrees C. This is always less than 100%.

The corrected state of charge is defined to be a percentage equal to 100 times the number of ampere-hours the battery can deliver at its present temperature at its specified rate, divided by its ampere-hour capacity at 25 degrees C. Note that this can be greater than 100%.

The initial battery state of charge can be entered manually from either the keyboard or the RS232C terminal. This can be based on a hydrometer reading of battery acid density, or simply an estimate. If it is wrong, the system will eventually correct it without damage to the battery. Default value at power-up is 50%.

The state of charge is increased by the number of ampere-hours flowing into the battery, and decreased by the number of ampere-hours flowing out of the battery. Rate of increase is modified by a tabulated coulombic charging efficiency which depends on state of charge. If the battery voltage exceeds expected limits, the state of charge is automatically adjusted to account for the variation.

EQUALIZATION

For every ampere-hour of discharge by the battery, one equalization fraction ampere-hour of extra or equalization charging is automatically programmed when energy becomes available and 100% state of charge has been reached. This is needed to bring all cells up to full charge and to stir the acid by generating small amounts of gas. This prolongs battery life.

If the battery goes through many partial charge and discharge cycles before equalizing, the total equalization charge is limited to the equalization total percentage to avoid excessive water usage.

During charging and equalization, the battery is allowed to rise to the equalization voltage. After equalization is completed, the battery voltage is limited to the float voltage, which is below the point of significant gassing and so uses up less water. This float level charge makes up for internal battery self-discharging.

ARRAY CONTROL

If the battery is not fully charged and equalized, the voltage limit is the equalization voltage. If fully equalized, the voltage limit is the float voltage. If there is no battery, a fixed motor voltage limit is used. Until reaching the voltage limit, the solar array charges the battery as much as the available energy allows.

There are two automatic modes of array control resident in the program. The first is discrete array control. This turns strings on, one per second as long as the battery voltage is less than 94% of its maximum limit. It makes no change until the battery voltage reaches 97% of its maximum limit. Between 97% and 100% of its maximum limit, strings are turned off one per second. Above 100% of maximum limit, all strings are turned off. The battery voltage used for this algorithm is averaged over 4 samples to minimize noise problems.

The second mode is maximum power tracking. The controller drives up to 10 power modules with a 20kHz pulse width modulated drive signal. The pulse width is set in 1/4 microsecond increments It is initialized to 0 and changed in small (1/4 microsecond) or large (2 microsecond) steps every 100 milliseconds. At each step, the total delivered power is calculated and compared with the power delivered at the previous duty cycle. If the power changed by less than 1.5%, and if no limiting conditions were encountered, small steps are used, otherwise big steps are used to speed up the process.

If the power level was found to be constant or increasing, the next step is taken in the same direction as the last. If the power was found to be decreasing, the direction of step in duty cycle is reversed. Therefore, the duty cycle is adjusted to the maximum power operating point, and

hunts there +/- one or two small steps, representing an operating point within +/- 1% of maximum power.

Switch S2, normally closed, is usually used as a motor thermostat, while S1 is often used as a water tank float switch level control. A manual switch in parallel with S1, normally open, provides a manual array shut-off function. If the charger current limit or battery maximum voltage limit is reached or if switch S2 is open, the duty cycle is always decreased. This converts the controller into a constant voltage or constant current power supply, normally used for the finishing charge of batteries or for motor starting without batteries. Also, if the inhibit switch S1 is closed, the duty cycle is set to 0, turning off the solar array.

Battery Load Control

The battery is assumed to be loaded by up to 5 separate load busses, with separate voltage sensing, current shunts in the negative load, and relay control responsive to the five optoisolator outputs of the controller. (Optoisolator ON= load ON.) These may in fact be auxiliary chargers as well as loads.

Each load bus is automatically monitored for excessive current. If current exceeds 120% of the nominal value (50mV on the current measurement shunt), the load is turned OFF, the audio and red LED alarms are turned ON, and a manual reset is required via keyboard or serial port. Under normal conditions, each load bus has two corrected state of charge thresholds; one below which the load is turned OFF (shed) and one above which the load is turnod ON (restored). By reversing the function of the optoisolator, an auxiliary generator can be properly controlled the same way. Each load or charger bus can also be manually controlled from the keypad or the serial port.

It is often desirable to use more energy if it's going to be a sunny day. This may be to avoid short cycles of load usage or simply to increase energy usage efficiency. Therefore, between 8AM and 12Noon, if the sunlight level is high enough to provide at least 10% of the maximum charger current limit to the battery, all the battery corrected SOC levels for load shed and restoration are decreased by a constant preset SOC, called DELTA SOC. This allows loads to turn ON earlier on a sunny morning than would otherwise be the case.

Product Storage Control

The MAC can perform a control strategy to allocate available energy into two different forms of storage. One of these is electrical energy stored in a battery. The other is a form of "product storage." This might be water stored in a tank, or thermal storage of cold in a refrigerator, freezer or ice stored in an icemaker.

To use this capability, it is necessary to be able to measure the amount of product stored. This product is assumed to be produced or pumped using energy from the same battery which is used to supply other electrical loads. To avoid over-discharge of the battery and to be sure the other loads get their share of energy, various state of charge (SOC) of the battery are defined:

This combination of trip points creates a set of four states of the controller, defined by the amount of product stored and the battery state of charge. By setting various values for the boundary parameters, various priorities can be placed on the use of energy.
during operation, a buffer or hysteresis of

Control Panel

The control panel has a keypad for manual inputs, a 4-1/2 digit LCD display for selected quantities, a set of red, yellow, and green LED's for quick status summary, and an audio alarm. There is also an emergency switch located at the bottom of the unit which, when turned OFF, will turn OFF all array strings and loads. When turned ON, it will restart the program.

The audio alarm will sound if any "circuit breaker" function (overcurrent on a load bus) is activated, or if an array fault is detected.

The red LED will light if any circuit breaker function is tripped or if bus NO.1 has been shed due to low state of charge (extremely low battery). The LCD "Low Battery" warning will also turn ON.

The yellow LED will light if load bus NO.5 has been shed due to low state of charge, but load bus NO.1 has not. This is intended to signal that energy is in short supply, but not an emergency. (Lower number loads usually have higher priority.)

The green LED is lit as long as the program is running. If a watchdog timer is not reset by the program, this LED goes out and the array is turned OFF.

The LCD display can be thought of as a multimeter which will display one of a menu of system parameters. The default display condition is battery state of charge, and after a data dump each half hour, it returns to this parameter setting. It can also display any array string voltage, any charger output string current, (not the array current, but the converted output from that string at the battery voltage level), the delivered string power to the battery, the battery voltage, current, or power; any of five load bus voltages or currents or powers, the battery temperature, one other temperature (used here for freezer product measurement), the pulse width, the equalization charge needed, the system zero reference voltage and 4.00 volt reference level, the temperature corrected state of charge, the time of day, or the software version number.

Self-testing

The keypad can also be used to change control

functions. To do this, the correct password must be entered. Password accessible functions include setting a new load and restore threshold for each load bus, setting initial state of charge and setting the manual control for each load bus ON or OFF.

Also, the unit can be placed in a test/calibration mode where data is refreshed but the states of charge, max power tracking and load controls do not automatically change. This allows them to be manually set and measurements taken. For example, a fixed pulse width can be set from the serial port, or a lamp test can be performed.

The display performs one more automatic test. If one of the charger power module output currents is less than a constant (1amp) below the average of all such currents, the "Continuity" segment of the LCD is turned ON. This means that one string of the array or one power module of the charger is either shadowed or broken. Examination of array voltages and currents will show the cause.

Besides these external tests, the unit performs an automatic test of its RAM and ROM access whenever it is started up. When running, any error causing the program not to execute properly will result in a watchdog timer fault turning off all loads and the solar array and causing the green LED to go out.

Serial Port Functions

The manual test/calibration mode was partially described in the previous section. However, with an RS232C terminal, much more extensive manual testing is possible. A standard debug monitor is implemented which can examine memory locations, insert bytes into memory, begin execution at a given memory location, insert or remove breakpoints, and download and program into memory.

A data dump of all system voltages, currents, temperatures, switch positions and states of charge is sent to the serial port every half hour or whenever requested. A printer there will provide data logging.

This powerful access allows many possible uses. The processor can be automatically tested during manufacture this way. A printer attached at the site can serve as a data logger. A telephone modem or other communication interface would allow automatic remote data logging or even, remote system control.

The use of a small RS232C terminal by a repair technician allows fault isolation and diagnosis beyond the capabilities of the keypad and display, since special test routines can be run. Software modification is greatly eased as well.

TEST RESULTS AND CONCLUSIONS

The battery charge control algorithm works as described. Its estimate of the available capacity is limited mainly by knowledge of the accuracy of the battery's rated capacity at a given discharge rate. This figure is reproducible only to about 10% accuracy, and is usually based on a fixed (80%) fraction of rated capacity at the end of a given time (5 years) or a given number of cycles. The initial capacity increases for a few cycles then slowly decreases with life. Therefore, the displayed battery capacity and the load management algorithm tend to be conservative by 10 to 20% over the first years of battery life. Long term low current operation is eliminated by internal battery self-discharge, typically 1% to 2% per week, and current affect errorrs of 0.1% of maximum, which is often a similar percentage per week. This is corrected whenever the battery is fully charged, so that batteries cycled daily or weekly are not affected.

The array control modes, both maximum power tracking and discrete switching, work very well and provide a nice tapered current finishing charge for a battery with very low water loss. The maximum power tracking with two step sizes is a real advance in the state of the art, as it provides a combination of less dither about more accurate tracking of a static maximum power point plus a faster settling time for a varying load or insolation. A chart comparing these performance figures is given here.

COMPARISON OF MPC FUNCTIONS

	State of the Art Equipment	MAC
Settling time +/-2%	3 sec	1 sec
Max Dither, stable load	3%	1%
Product of above	9	1

This means that, for example, a volumetric pump or other slowly cycling load can be dynamically matched to the solar array with a reduced need for expensive or inefficient load-levelling mechanisms such as large flywheels, batteries, etc. This opens up additional applications for the controller.

Load management in response to battery state of charge is very good. It is free of the chattering and instability characteristics of many voltage-related load management schemes. The algorithm for product storage and apportioning energy to several types of loads works as expected. However, its sophistication makes it difficult for a user to verify that it is operating properly, and this may make it less popular than other approaches based solely on battery status. Instrumentation of the system using the keypad and LCD display is very effective. A permanently posted list of command codes on the unit near the keypad was found to be useful.

Data logging via the RS232C terminal to an inexpensive printer is very helpful in village systems. Of less use in smaller applications, it is quite helpful for maintenance or fault diagnosis using a small hand held battery-powered RS232 terminal. The possibilities inherent in a phone coupler or other communications port for remote system control have not been explored, but they are potentially very interesting. The self-test functions of the controller are an effective means of allowing unskilled personnel to monitor a complex photovoltaic system.

In conclusion, the microprocessor automatic controller works as well as, or better than, any existing photovoltaic system control equipment, and can be adapted to a wide variety of systems simply by plugging in an EPROM. This makes it a very attractive controller for photovoltaic systems where large size (over 2kW), remote location or special control requirements justify this type of unit. This type of controller could be readily adapted for space applications.

Acknowledgement

The fine efforts of Dr. Tom Maier and other members of the Mellon Institute Computer Engineering Center, who developed the software for this project were essential to the success of this work.

APPENDIX 2

SPECIFICATIONS OF THE SOLAR CHARGE CONTROLAR™ FROM PSI.

SOLAR CHARGE CONTROLAR™

From: Pulfrey Solar Incorporated
4030 West 35th Avenue, Vancouver, B.C. V6N 2P3, Canada
Tel: (604) 263-6780

MAIN FEATURES:

The CONTROLAR™ is a CMOS 6805-microprocessor-based battery charge controller for use in 12V PV systems rated up to 1000Wp. It uses the charge integration method for estimating the state-of-charge (SOC) of lead-acid batteries. This method of SOC estimation is considerably more accurate and reliable than the traditional methods based on measurements of either terminal voltage or specific gravity.

The CONTROLAR™ regulates the charge flow to the battery and operates in three, automatically-determined modes, namely: charge, equalize and float. In the charge mode, battery charging proceeds at the available array current level. In the equalization mode, a charge equal to 5% of the cumulative discharge since the previous instance of full-charge, up to the limit of 5% of the battery capacity, is allowed. After completion of the equalization charge, the battery enters the float mode and trickle charging proceeds at a regulated battery voltage of 14V.

The CONTROLAR™ continuously displays the present charging mode and the %SOC on its LCD.

The CONTROLAR™ is modular in nature. The basic unit comprises one logic board and one power board and is rated at 20A (250Wp). Up to three more power boards can be added to increase the rating in 20A increments up to 80A (1000Wp). Interconnection of the boards is easily made via standard connectors.

ADDITIONAL FEATURES:

* CPU operation at a clock frequency of 4MHz, allowing for sampling of the battery current and other system parameters every 1.024 seconds.
* LCD display, on command, of system parameters: battery capacity, charge/discharge current, cumulative discharge, terminal voltage, battery temperature.
* Low SOC limit; automatically sheds load when user-selected low SOC limit is reached. Load is automatically re-connected when SOC returns above the low limit.
* High charging voltage limit; automatically switches to float mode and regulates voltage to 14V if the terminal voltage during normal charging exeeds 17.5V.
* Load-shedding and power board relays use silver-cadmium oxide contacts for long life and rated operation to -55C.
* Temperature compensation and battery charging inefficiency factors can be preprogrammed into the CONTROLAR™'s EPROM.
* Suppression of voltage surges by varistors.
* Reverse leakage protection by Schottky diodes.
* Compatible with battery capacities up to 2048 Ah.
* Housed in a NEMA class 4, steel, weather-tight enclosure.

SPECIFICATIONS

Array voltage (nominal)	.....	12 V
Array current (maximum)	.....	20 A (1 power board)
	.....	40 A (2 power boards)
	.....	60 A (3 power boards)
	.....	80 A (4 power boards)
Charge counter resolution	....	11.1 microamp-hr (0-10A, single power board)
	....	44.4 microamp-hr (10-20A, single power board)
	....	44.4 microamp-hr (0-40A, four power boards)
	....	177.6 microamp-hr (40-80A, four power boards)
Battery capacity	....	up to 2048 A-hr
Low SOC cut-out	....	0-100% (user-selectable)
Battery voltage limit	....	17.5V (automatically regulated)
Float voltage	....	14 V
Standby current drain	....	28 mA (20A model, without load-shedding relay)
	....	93 mA (20A model, with load-shedding relay)
	....	40 mA (80A model, without load-shedding relay)
	....	300 mA (80A model, with load-shedding relay)
Temperature range	....	-10C to +70C (with standard chips)
	....	-40C to +80C (with extended temp. range chips)
Physical size	....	16in.x14in.x6in. (80A version)
Mass	....	30 lb. (80A version)